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JOURNAL
OF THE
AMERICAN SOCIETY OF NAVAL ENGINEERS

VOL. 58. NOVEMBER 1946. No. 4.

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GENERAL NOTES ON AN INSPECTION TRIP TO EUROPE IN OCTOBER-DECEMBER 1945.

BY CAPTAIN HAROLD E. SAUNDERS, U. S. NAVY.*

INTRODUCTION.

The pages of American periodicals have for the past year or more been crammed with stories written by people in all walks of life who have made inspection trips to the European Theater of Operations and who have related their experiences for the benefit of their less fortunate brethren who could not visit this area and see the interesting sights with their own eyes. The author has no desire to cram them further with more stories of the same kind. He will do his best to keep off subjects previously covered, both by words and by pictures, and he will endeavor to concentrate on a few new features which are of particular interest to

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members of the American Society of Naval Engineers and to readers of this JOURNAL.

The author's trip to Europe was made as the result of a special directive from the Chief of the Bureau of Ships, Vice Admiral E. L. Cochrane, U. S. N., who desired to have the Technical Director of the David Taylor Model Basin obtain an overall and comprehensive picture of the research program carried on by the Germans prior to and during World War II.

At the outset of the trip the author's primary interest was in test facilities and equipment rather than in the research programs being followed or in the personnel being used by the European Nations; the test facilities, at least in Germany, had to be seen while they were still in existence, whereas the programs could be studied from technical reports. It soon became evident, however, that even though Europe had a greater proportion of available scientific personnel than the United States, the problems posed by a shortage of trained personnel were no less pressing there than on this side of the Atlantic.

As an aid in planning postwar research of general interest to the Bureau of Ships, the Navy Department, and other government departments, and of particular interest to the Taylor Model Basin, specific information was sought from Germans and others on three subjects:

a. The trend which research would have followed had there been no interferences from shortage of personnel, lack of funds, or lack of materials, and had the war progressed favorably for the nation in question.

b. The changes or modifications which would have been made in testing facilities or apparatus had it been possible to design and build them over again, based upon the lessons and the experience of World War II.

c. The methods in use and the procedure being followed to recruit and to train scientific and technical personnel in all classes and categories.

CONTINENTAL MODEL BASINS.

On the Continent, the author visited model basin establishments in Hamburg and in Berlin, Germany, in Wageningen, Holland, in Paris, France, and in Rome, Italy (including Guidonia, just outside of Rome). Other basins were visited in Haslar, England, and in Teddington, England. Because of lack

of time visits were not made to model basin establishments in Norway, Sweden, Spain, and Russia, nor to several other smaller model basins in Germany, Holland, England, and Scotland.

At Hamburg there were four, and at Haslar and at Teddington there were two separate model basins in each establishment. In nine of the thirteen separate model basins listed, self-propulsion tests as well as resistance tests of ship, motor boat, and flying boat models could be made.

The Paris Model Basin, the Bassin d'Essais des Carènes, was visited twice. In the seven-week interval between visits, the work and activity had picked up appreciably, and a new large variable-pressure water tunnel, left unfinished since 1939 and 1940, had been dusted off and was being placed in operation.

The most interesting test facility at Paris, and the only large facility of its kind in the world, is a circular turning basin about 220 feet in diameter, housed in a building that has a domed concrete roof with a large circular opening in the center, much on the style of the famed Pantheon at Rome. In the center of the circular basin itself is a concrete island carrying a large pivot, around which revolves a steel truss structure whose outer end is carried by 8 rubber-tired wheels running on a circular track around the perimeter of the basin. A dynamometer on the rotating arm measures the drag, side force, and yawing moment on a ship or torpedo model as it is caused to move in a circular path around the basin. The advantage of this type of facility is that the model can be towed at drift angles greater or less than the equilibrium value, to obtain basic data for predicitng the turning characteristics.

So far as could be learned, this most unusual basin had been planned by M. Barrillon, Director Emeritus of the establishment, who was still spending half of each day in an office where he had labored for many years. M. Barrillon had not intended that routine resistance tests be made on ship models in a circular path but that special measurements be taken on models of ships, as well as of torpedoes, to obtain basic data which would afford a closer insight into the turning characteristics of water craft.

The Paris Model Basin staff exhibited with some pride a new rudder dynamometer which they had recently built to measure the forces on rudders carried by a model. They were also engaged in systematic experiments on the rolling of ships, using schematic models in a rather wide range of sizes. An excellent

composite photograph of a ship model running into a series of waves was furnished the author through the courtesy of M. Barrillon and Captain Brard, the present Director of the establishment. It is reproduced here as Figure 2.

The waves in the large rolling basin are generated by an ingenious "shovel" type of wavemaker also devised by M. Barrillon. This wavemaker is supposed to generate a wave more nearly trochoidal than that in any other model basin. Whether it actually does this or not the ponderous machine sends out the waves with an effortless ease characteristic of the output of any equipment that is well designed and well built.

The leading model basin establishment on the Continent prior to V-E Day was the Hamburgische Schiffbau Versuchsanstalt (HSVA) at Hamburg. This plant, which comprised four model basins, two variable-pressure water tunnels, and a large new maneuvering basin, was at the time of the author's visit being dismantled and destroyed by German prisoners of war under the direction of the British occupying forces.

Horizontal lines of holes were being drilled into the model basin walls at midheight and filled with liquid oxygen charges to split the walls under the carriage tracks. The basins were being filled with rubble from wrecked buildings in the vicinity, with the idea of flooring over the top of the basins and using the buildings for barracks for displaced persons in the Hamburg area. The two water tunnels had already been dismantled and were enroute to England, where they are to be set up, it is understood, at the National Physical Laboratory at Teddington and the Admiralty Model Basin at Haslar.

Although without any physical plant, Doctor Kempf, the Director of the Hamburg Model Basin staff, was still holding periodic staff meetings in the apartment of one of his engineers, in the vain hope that somehow or other they could find some place in which to continue their scientific work.

The model basin at Berlin had been severely bombed and burned out on several occasions and was in a state of complete disrepair. Figure 3 shows the carriage, now rusty and neglected, and the basin building with gaping holes in the roof.

The triangular frame of the high-speed carriage, which the author particularly wished to inspect, could not be found It was reported that this frame was built of Electron metal, an alloy of magnesium, and that it had burned up completely in the

fire following one of the bombings to which this plant was subjected.

At Wageningen, in the Netherlands, the Germans had removed the motor generator and the driving motors from the large variable-pressure water tunnel belonging to the model basin establishment and had destroyed some essential parts of the control equipment for the operation of the main towing carriage over the model basin. Fortunately, however, through scraps of information obtained from British and other sources, the Director, Mr. L. Troost, had been able to learn what the Germans had done with this machinery. Thanks to the methodical German mind, when the last paper was found it listed not only all the machinery which had been stolen but the city and even the warehouse in which it was located!

Just prior to the author's visit, Mr. Troost had returned from the Ruhr district, where he had actually seen his equipment, covered with dust but still intact.

The Nederlandsch Scheepsbouwkundig Proefstation atWageningen, as it is called in Dutch, is close to the Arnhem area, where severe fighting occurred in the airborne invasion east of the Rhine in September 1944. Shells and bullets of all descriptions, from both Allied and German guns, flew over this area in both directions for about five weeks before the Director and his assistants could evacuate their model basin personnel and families to Utrecht, in a safer part of the Netherlands. The Director's home, at the time of the author's visit to his family, still showed bullet holes in the windows, patched with narrow strips of glass. The entire wood floor of his dining room had been sawed out around the edges and removed bodily by the Germans to form a temporary wall for some of their trenches in the vicinity.

At the time of writing, the Netherlands Model Basin is again in operation and is picking up its contacts anew with the outer world.

After leaving Paris and seeing one model basin after another out of commission, bombed, or burned, it was a welcome experience to ride on the carriage of the Vasca Nazionale, the large model basin establishment in Rome. The building housing the model basin has a vaulted concrete arch roof, something like the famous arch roof at Carderock. The latter, despite its unusual construction and the care taken in its erection, had given some trouble because of condensation on the under side of the metal

flashing over the expansion joints. The Taylor Model Basin staff had been worried about water dripping down on the rails but in the arch roof of the basin building at Rome it was possible to see daylight through some of the expansion joints and it was raining through them! From these and other observations abroad the author could understand that much has been learned about the construction of buildings in the past 15 years.

It has always been necessary at Rome to make the models out of wood because of the high average temperature in this vicinity throughout the year. One look at the difficulties which the staff were having with European pine and not-too-modern glue brought forth an offer from the author to help them out. Information on gluing technique and samples of modern glue have since been sent to Doctor de Santis at Rome.

Due to the complete cessation of naval building and merchant vessel construction in Italy the Rome Model Basin was working only on a few models of small coastal and fishing vessels.

A number of photographs were made of interesting and ingenious devices in the Rome model shop, and upon its departure the author's party was presented with a complete set of the publications of the Vasca Nazionale, 11 large volumes in all.

The splendid high-speed model basin of the Italian Research Institute at Guidonia, about fifteen miles east of Rome, which was visited with Doctor R. de Santis of the Rome Model Basin as a guide, had suffered the fate of the remainder of this modern and outstanding research establishment, which worked on aerodynamical and many other research problems. Before their evacuation from this area, the Germans had taken away every piece of machinery and apparatus, every instrument, and every article which the Italians or the United Nations might use to resume work here, including the furniture, the office fixtures, and the pictures on the walls. They had then sent their demolition teams through the establishment and had done major structural damage to the buildings, mainly by blasting out the columns and other supports.

The Germans had removed the wheels, the gearing, the motors, and the dynamometer from the high-speed towing carriage and had then dropped the heavy roof structure down on top of the carriage frame by blowing out the wall supports. About 300 feet of roof at midlength of the basin had been dropped down

into it, as shown in Figure 4, and the basin walls had been badly damaged at several other points.

It was nevertheless possible to make sketches and to take photographs of the ingenious joints which the Italians had developed for the heavy built-up rails laid alongside this basin. This joint embodied not only a diagonal scarf in the rail head, similar to that in the rail joints at the Taylor Model Basin, but a long diagonal scarf in the sides of the rail, to provide a continuous support for the carriage guide wheels.

The wave absorber along each side of the basin was a sloping concrete shelf approximately at the waterline, poured integral with the wall. In this respect it was similar to the wave absorber around the circular turning basin at Paris, but in addition it had elongated openings at the back of the shelf, next to the wall, not to be found in the Paris basin. These slots show clearly in the photograph, Figure 5.

More than any other model basin visited in Europe, the high-speed basin at Guidonia gave one the impression of sound basic design, of sturdy construction, and of almost faultless execution. Even through its wreckage there shone the spirit of a group of engineers who set out to build a masterpiece, one that would survive much more than the Germans were able to do to it in this war.

In this respect it differed markedly from all other model basins in Germany, Holland, and Italy. These showed, literally as well as figuratively, the hand and name of Doctor Friedrich Gebers, who had designed the Vienna tank over 30 years before and who made every one thereafter almost a Viennese copy of it. The whole setup almost shouted the words "Système Dr. Gebers" long before one got close enough so that these ever-present words could be read on the nameplates!

With nearly twenty model basins in operation in Europe before the war it is not surprising that, even with limited staffs at some of these establishments, it was possible to carry on much more research in ship form and propulsion there than had been possible in the United States in prewar years. With a preponderance of about ten to one in the number of model basins which could conduct self-propulsion tests on ship models, it is likewise not surprising that the Taylor Model Basin has not been able to keep up with the work it has been called upon to do in this country for private firms as well as for government activities. The facts that

the United States is one nation instead of forty-eight, that building and machinery costs are higher here, and that there is a greater shortage of scientific and technical personnel here than in Europe, seem to be the principal reasons why it has not been possible to build other large model testing establishments in the United States.

Variable-Pressure Water Tunnels.

The model basin establishments of Europe, with their many basins of varied sizes and uses, were likewise rich in variable-pressure water tunnel equipment for cavitation tests of propellers and subsurface bodies. At the HSVA at Hamburg the first such tunnel in Europe had been installed, dating from about 1931, which served as the pattern for most of the other variable-pressure water tunnels in Europe. The hand of Doctor H. Lerbs showed plainly in the design of each of these tunnels, as the hand of Doctor Gebers had shown in the model basins and carriage designs, but there was here an appreciable degree of progress from tunnel to tunnel, conspicuous by its absence in the model basins.

One of Lerb's latest designs was to be found in the supertunnel at Hamburg, which had a test section approximately 8 feet wide and 4 feet high, but which was not yet fully completed in 1945. The maximum speed of this tunnel was, however, only about 16 knots. The large tunnel at Wageningen, with a test section about 40 inches square, had been in operation before and during the war, employed principally in testing propellers.

There were other large variable-pressure water tunnels at Paris, Pelzerhaken, Haslar and Teddington. A smaller variable-pressure water tunnel had been in operation at the Kaiser Wilhelm Institute for Hydraulics at Göttingen. The latter was a so-called "free-jet" water tunnel which was claimed to operate at the lowest cavitation number of any tunnel in existence. At the huge Luftfahrtforschungsanstalt at Völkenrode, which was exclusively an aerodynamical research center, there was, strangely enough, a small water tunnel which had been used for the study of the flow over small plastic airfoils. Figure 6 illustrates this test facility.

The German scientists had found that regions of high local velocities on parts of the high-speed aircraft could be made prominently visible by placing models of these parts in a variable-pressure tunnel and creating cavitation around them in the same

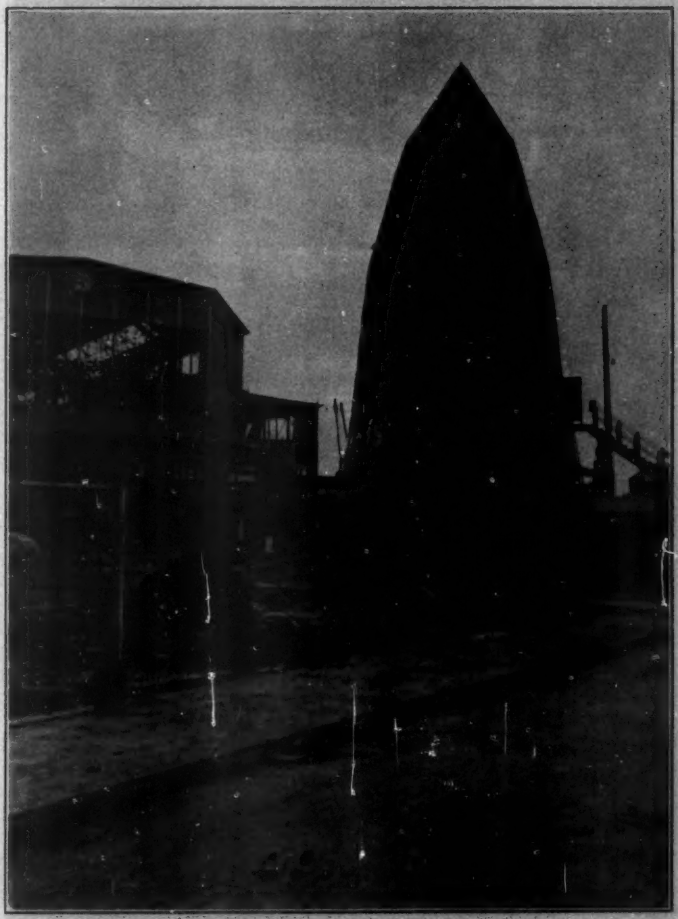


FIGURE 1—BEEHIVE TYPE OF AIR RAID SHELTER IN THE DESCHIMAG SHIPYARD, BREMEN.

Judging by the phenomenal resistance of tall chimneys to bomb blast, not only in Germany but in Hiroshima and Nagasaki, a shelter of the type shown here may prove to be the most resistant type of above-ground structure in an atomic age.

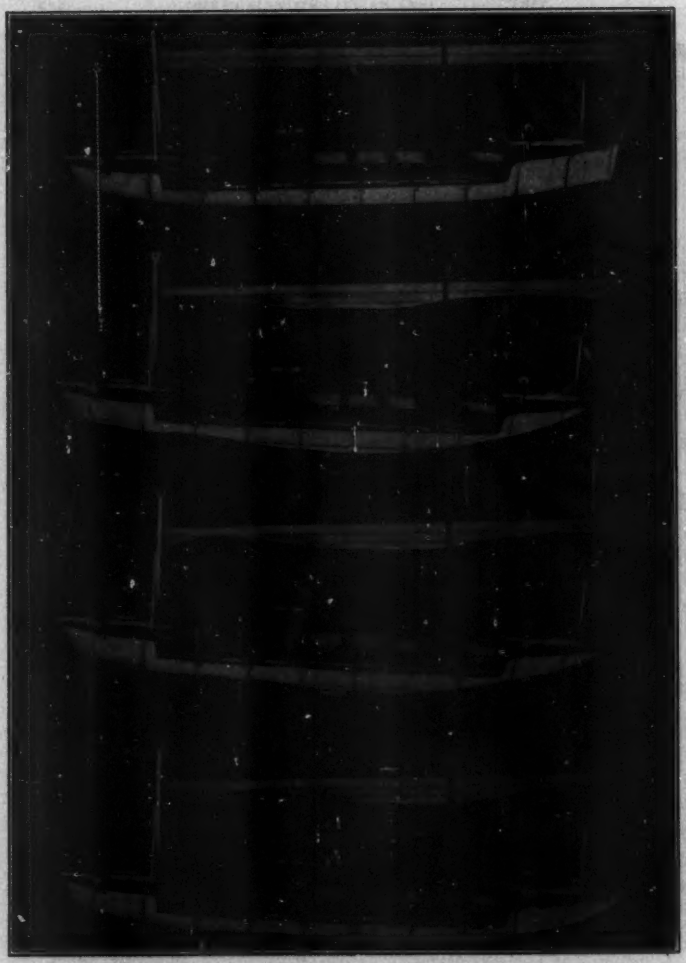


FIGURE 2—A MODEL IN WAVES AS PHOTOGRAPHED AT THE PARIS MODEL BASIN.

This excellent and unusual set of photographs was furnished the author by the courtesy of the Director, Captain Brard.

FIGURE 3—WHAT IS LEFT OF THE BERLIN MODEL BASIN.

The light in the basin building in the background comes through bomb holes in the roof. The arch over the carriage carries the tracks of electric railway lines.

FIGURE 4—THE HIGH-SPEED BASIN BUILDING AT GUIDONIA, ITALY.

The Germans demolished about 300 feet of the building at midlength of the basin, blew out all the windows, and blasted out sections of the basin walls and tracks.

FIGURE 5—WRECKAGE OF THE HIGH-SPEED BASIN AT GUIDONIA.

This is the way the Germans left it after stripping the carriage and dropping the roof down on the frame. The wave absorber ledges with their slots are clearly visible here.

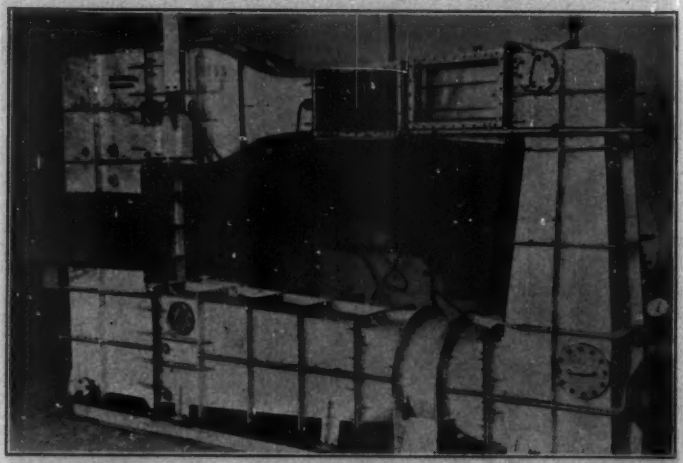


FIGURE 6—THE SMALL WATER TUNNEL AT VOLKENRODE, GERMANY.

This tunnel, used by the Germans for research work on airfoil sections, is only about 6 feet high overall. A glass plate forms the entire front of the test section, shown as the dark area in the photograph.

FIGURE 7—FULL-SCALE MODEL OF ARADO 396 FUSELAGE.

The plexiglass nose was tested for strength by towing the assembly under water in the large basin at Hamburg.

FIGURE 8—SQUARE STEEL TUBING IN LARGE HAMBURG CARRIAGE FRAME.

The square tubes were made up by welding together two thin U-shaped plates along the edges of the free flanges.

FIGURE 9—THE ACOUSTIC TANK AT PELZERHAKEN, GERMANY.

The tank was empty when this photograph was taken. One of the bridges hanging from the roof trusses may be seen in the background, with the car suspended from it just inside of the far end of the tank.

FIGURE 10—GERMAN NON-REFLECTING LINING FOR ACOUSTIC TANKS.

This lining, called by the Germans "Fafnir" or dragon's-teeth lining, is formed of rubber wedges held by metal strips. The rubber wedges are 4 inches long overall, 2 inches wide at the base, and 9/16 inches thick. So far as known, there were a multitude of horizontal rows of this lining on each wall of the tank, spaced about 1½ inch apart.

FIGURE 11—THE ROLLING MODEL AND TANK AT RAVENSBURG, GERMANY.

The model is in the center of the photograph with the rolling tank extending outward on the right and left. The water surfaces alongside the model do not show up clearly because of the reflections from overhead.

FIGURE 12—THE SPERRBRECHER "MINERVA" IN KIEL HARBOR.

This vessel had been brought from Copenhagen before her conversion to an ocean-going minesweeper had been fully completed. The dark areas are the portions of the hull covered by the cables forming the magnetizing coils; these areas had been only partially sheathed with steel which had not been painted.

FIGURE 16—SIMPLE GERMAN RESEARCH FACILITIES AT STUTTGART-RUIT.

The car in the foreground, filled with gravel, is the protective cover for a test pit underneath. Simplicity and Nature provide excellent natural camouflage.

way that voids had been caused to form around model propeller blades for many years previously.

The large variable-pressure water tunnel at Paris was different in many respects from any other existing installation. The French, typically enough, had developed their design from what appeared to be fresh viewpoints, and it will be most interesting to see what results they achieve when they have it in full operation.

The newest variable-pressure water tunnel seen in operation in Europe was at the Escher Wyss Plant in Zürich, Switzerland, intended primarily for the testing of variable-pitch reversible propellers. This tunnel represents an even greater departure from current practice. It is of the open-circuit syphon type, in which the lower horizontal channel is in the form of a large open tank, intended apparently as a stilling chamber. It will likewise be interesting to watch the performance of this unusual tunnel after the usual shake-down runs and calibration.

The interior surface of the Escher Wyss test section was painted in brilliant white which showed no signs of discoloration after three months of operation. A stroboscopic spark system illuminates the rotating propeller in the manner of the Strobotac equipment used in tunnels in this country.

In all there were eleven variable-pressure water tunnels in Europe as compared to five in the United States, a reminder that our country is by no means the leader in all branches of scientific research that many Americans believe.

Testing of Airplane Structures in The Hamburg Model Basin.

The many and varied problems of World War II had brought to the Taylor Model Basin a volume and variety of tests which it was felt had never been experienced by any ship model testing establishment in the past. However, when opportunity was afforded to visit the HSVA at Hamburg it was found that the Germans had extended the scope of their work several steps further in one direction, namely to include the towing of full-scale components of airplanes in the water to test their rigidity and structural strength. Owing to the large size of these components, one of which is shown in Figure 7, and to the high speeds at which they traveled in service through the air, the forces required to tow them through the water by the carriage were much greater than for routine work, and the normal accelerating and decelerat-

ing rates had to be stepped up to provide a reasonable length of run in the existing basin at Hamburg.

Finding it not possible to put any more overload on the four electric driving motors of the large towing carriage, the Germans had mounted two airplane engines with air propellers on top of the carriage frame and had added two rockets to supply a considerable amount of thrust still lacking with the electric motors and gasoline engines. Firing the rockets inside a basin building with many glass windows in the walls presented unexpected problems for the Hamburg personnel. Timing the gasoline engines and the rockets so that they would exert their maximum thrust at the exact point in the accelerating run at which it was most needed required all the ingenuity that even German engineers could muster.

The method of towing full-scale airplane parts in water as a check on their strength and rigidity was found so useful that at the end of the war this procedure was being extended to the towing of full-scale airplanes. The span of the wings was limited by the 53-foot width of the basin but by turning the airplane upside down and producing negative lift it was possible to develop loads on the various parts up to the buckling point of the structure.

Since the existing towing carriage was not sufficiently strong and rigid and could not support its own weight plus the negative lifts required, a crude but strong trailer carriage, ballasted with water-filled tanks and towed behind the existing carriage, was used for attachment of the airplane components. This so-called "Brutal" carriage was employed as a stop-gap measure only. A new strong and heavy single carriage was being constructed for this specific work. This new carriage when completed was to weigh at least 220,000 pounds, more than twice as much as any towing carriage in existence.

The basin building and the deep water basin at Hamburg were both lengthened by about 330 feet, to provide for the necessary accelerating and decelerating runs. At the starting end of the basin extension there was provided a sort of dry dock with a removable gate. This was intended to make it possible to unwater the dock and to suspend the full-scale airplane in its inverted position under the new carriage while attaching and adjusting it. This work completed, the water was to have been admitted to the dock and the gate removed, whereupon the

carriage would have then been ready for towing the airplane through the basin.

The structure of this huge carriage was of the hollow welded tubular design exemplified by the Taylor Model Basin carriages, but most of the tubes, instead of being of circular-section seamless tubing, were of square section, built up by welding together the free edges of two U-shaped channel sections. Figure 8 is a view of one of the large girders for this carriage. So far as could be seen, there was no reinforcement of any kind within the square tubes, which were of steel about ⅛ inch to 5/32 inch thick.

Acoustic Testing Tanks.

One of the brand-new developments of World War II, so far as model basin technique was concerned, was the necessity for making acoustic measurements on or around models towed through the water, generally in the completely submerged condition. To meet this requirement the Germans had built at their Communications Research Establishment at Pelzerhaken, on the northwest shore of Lübeck Bay, a special tank for acoustic experiments.

This tank was of concrete, 328 feet long by 131 feet wide by 13.1 feet deep, filled with sea water (not fresh water, as is customary in most model basins) pumped in from the nearby bay. The tank was enclosed in a building having roof trusses 150 feet or more in length, spanning the entire width of the basin plus a walkway on each side. A general view of a portion of the interior of this basin and building is shown in Figure. 9

There were two long bridge structures, approximately 350 feet from end to end, each mounted on about 20 pairs of wheels and tracks on the underside of the roof trusses, so that they could be moved back and forth across the width of the tank while remaining parallel to the long diemension of the tank. Each bridge structure could be moved independently of the other in a transverse direction by hand; there was no provision for automatic or power traverse, to move it in the manner of a towing carriage.

Under each bridge there was suspended a light aluminum car carried by four rubber-tired wheels overhead which ran on wooden tracks on the bridge, isolating the car from any noise or reverberations which would otherwise be caused by and transmitted through steel rails and steel wheels. The car under each bridge was made to run back and forth along the entire length of

the bridge by a system of cables and pulleys from a fixed winch. This operation was independent of the transverse position of the bridge.

Under one car there could be suspended a model or other object representing a target, with or without a sound-making device, while under the other car there could be suspended a hydrophone or other apparatus to represent an underwater weapon which was endeavoring to locate or to attack the target.

It is reported that the entire surface of the four vertical walls of this tank was covered with a special nonreflecting lining which made the tank very nearly the equivalent of the open sea so far as reflection and background noises were concerned. A sample of non-reflecting lining composed of rubber wedges or triangles closely spaced and pointing into the tank was picked up by the author in another building at Pelzerhaken; Figure 10 is a photograph of this sample. At the time of writing it has not yet been determined whether this sample represents the Pelzerhaken acoustic tank lining, which had been completely removed from the tank before it was visited by any American officers of the U. S. Naval Technical Mission in Europe.

Judging from literally tons of apparatus, instruments, models, hydrophones, transducers, and miscellaneous material lying about in this building, the Germans must have carried on a great deal of active research there during the war. Just how much of it related to the German acoustic torpedoes is not known, but a collection of Asdic and Sonar gear captured from the British was mute evidence that they had been keeping up as well as possible with the developments in the underwater acoustic apparatus made by one of their enemies.

Regardless of what they had done at Pelzerhaken, the large acoustic tank represents a very definite step in the development of modern comprehensive test facilities. It cannot be denied that the Germans stole a march on the rest of the nations when they planned and built a facility which is still, a year after V-E Day, the only one of its kind in the world.

At the Atlas Werke in Munich, which developed the latest model of the German acoustic torpedo, was found a small calibration tank about 6 feet square and 6 feet deep which was completely lined with thick rubber wedges, similar to those shown in Figure 10, and which was likewise said to be the equivalent of the open sea for a very considerable range of sonic frequencies.

A look at the inside of this tank, with its multitudinous rubber wedges, each painted red for some reason not yet determined, gave one a creepy feeling which explained in part the name "Fafnir" (dragon) applied by the Germans to this lining. One would certainly wish to be delivered from the mouth of a dragon which had such forbidding teeth spaced so closely together.

During the visit to the Atlas Werke, the German guides related a yarn which, if true, may have had some bearing about the subsequent development of the German acoustic torpedo. They said that when the Bismarck was hit by three British torpedoes under the stern in the famous battle in May of 1941, they felt sure that the British must have had some acoustic torpedoes to accomplish this remarkable (and disastrous) feat!

Ship-Stabilization Tank.

At Ravensburg, in the southwestern corner of Germany not far from the Swiss border, there is a subsidiary Escher Wyss plant owned by the Swiss but apparently operated by them for the Germans during the war.

At this plant there is a large tank built specially for ship-rolling and ship-stabilization experiments. Like the acoustic tank at Pelzerhaken it is, so far as known, the only one of its kind in any country. This tank is about 65 feet long and 28 feet wide, and floating in it is a huge box-shaped model of steel about 60 feet long by 10 feet wide by 8 feet high. The model has the cross section of a ship but it is all parallel middle body, with no bow and no stern. There is a large centering pin projecting from each end of the model, which slides up and down in a vertical guide at each end of the tank and keeps the model in the middle of the tank.

When ballasted to represent a loaded ship, the model weighs about 60 tons. As illustrated in Figure 11, it is large enough and heavy enough so that an operating and observing crew can ride the model during a rolling test. By shifting the blades on a variable-pitch reversing propeller mounted in an opening in a vertical partition in the tank, directly under the model, the water level at the sides of the model could be made to rise and fall at any desired rate, thus causing the model to roll.

The use of compressed air for shifting water back and forth in port and starboard anti-rolling tanks to counteract the roll had been tried and given up at Ravensburg, apparently long after it

had been found impracticable elsewhere. The German Escher Wyss research group, which was apparently a separate entity in the plant and was housed, with the tank, in a building of its own, had been working recently on activated tanks in which the water was transferred from side to side of the ship by the action of a variable-pitch reversible Escher Wyss propeller.

Using the hand control, the author and his party were able to roll the model from side to side up to an angle of 24 degrees each way, and then (if they were skillful) to bring it to rest momentarily in the surging water. No automatic control was demonstrated during the visit. Quite obviously, Escher Wyss was not interested in ship stabilization as such, but as a possible market for their reversible propellers.

While this rolling tank at Ravensburg is indeed novel and unusual, with no known counterpart, and while it causes the model to roll in the same general manner as the waves of Nature cause a ship to roll at sea, it has several drawbacks and defects, which should not be repeated in a new facility built elsewhere;

a. the water level on each side is not uniform, along the length of the model,

b. the model should be held in line by something less artificial and less restrictive than the centering pins in use on this model, and

c. the model is too limber, especially in its resistance to torsional deformation.

Ocean-Going Minesweepers.

There were inspected at Kiel two ships which belong to a class which is interesting and unique but which has had relatively little publicity during and following the war. This is a class of sea-going minesweeper called "Sperrbrecher" (literally barrier-demolisher) by the Germans, equipped to sweep acoustic and magnetic mines in North Sea weather too heavy to permit small minesweepers to keep the sea, much less to stream their gear.

These sperrbreckers, at least the two visited by the author and his party, were medium-sized high-speed cargo vessels, large enough to operate in practically any North Sea weather. They were converted into giant magnets by copper cables wrapped around their hulls, through which large electric currents were passed, and were equipped with acoustic minesweeping devices.

One of these ships, photographed by the author in Kiel Harbor in a partly converted state, is shown in Figure 12.

The dark area abreast the well deck forward is the unpainted steel sheathing covering the main coil, comprising 52 turns of stranded copper cable about 1 1/16 inch in diameter, having an area of about 1.2 million circular mils, wrapped entirely around the hull on the outside and carried across the well deck. There are about 6 miles of this cable in the main coil of one ship.

A secondary or auxiliary coil is passed around the forward part of the ship at an angle of 45 degrees, with the leads brought through the side of the ship below the forecastle.

Direct current was supplied to these coils by an array of diesel-driven generators aggregating about 1000 HP on each ship. The two ships inspected had a conglomeration of engines and generators of various types, makes, and sizes, depending undoubtedly upon their availability at the time of the conversion.

Whereas practically all the wiring and bus bars in new shore installations throughout Germany were found to be of aluminum, the sperrbrecher coil cables were of copper, apparently of the best quality. The cables were covered solely by a single-layer rubber sheathing about 5/16 inch thick, making them about 1 11/16 inch in diameter overall. The rubber, like the copper, was apparently of excellent quality. The Chief Engineer of one sperrbrecher which had been operating for 2½ years stated that the insulation resistance of his main coil was still from 0.5 to 2 megohms! Apparently when the Germans really needed critical material in a spot they used it, no matter how scarce it was.

The standard inspection procedure for parties such as the author's would have been to saw off about two feet of this excellent cable and insulation and to bring it home. This rough-and-ready method was not adhered to in this instance, however, because the U. S. Navy was about to take over these two ships for sweeping mines in Japanese waters.

Cycloidal Vertical-Blade Propellers.

It is not generally recognized nor well remembered in this country that the cycloidal vertical-blade propeller was first invented and tested by Professor Kirsten of the University of Washington in about 1923. Professor Kirsten's propeller was a fixed-pitch design in which the direction of thrust could be varied but in which the blades were always working at the same pitch

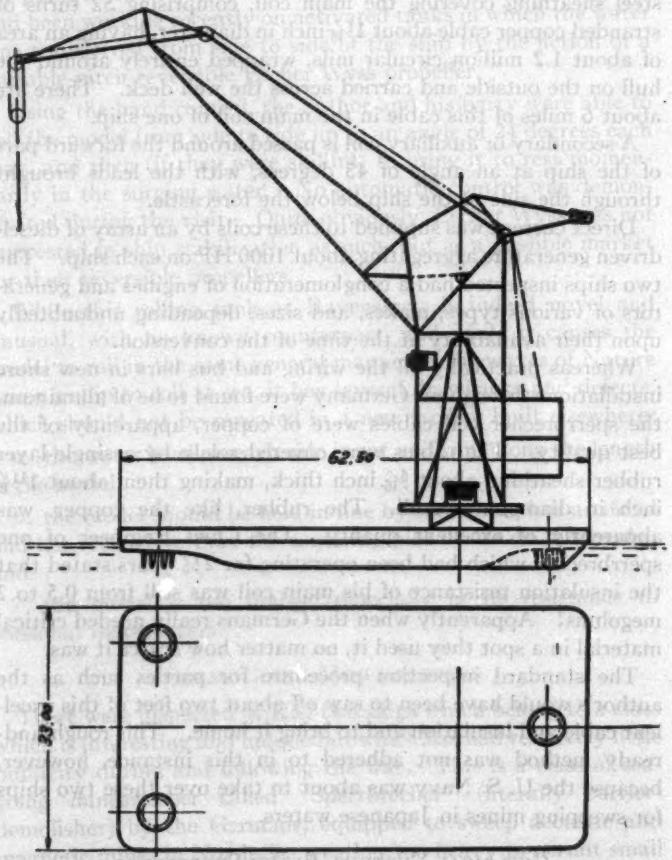


FIGURE 13—A HUGE FLOATING CRANE WITH THREE VOITH-SCHNEIDER PROPELLERS.

The dimensions given here are in meters. The extreme maneuverability and handiness of a craft of this kind is shown by the diagrams of Figure 14.

angle. The Germans modified this design to give it a variable-pitch feature so that the propeller could exert any desired amount of thrust up to the maximum.

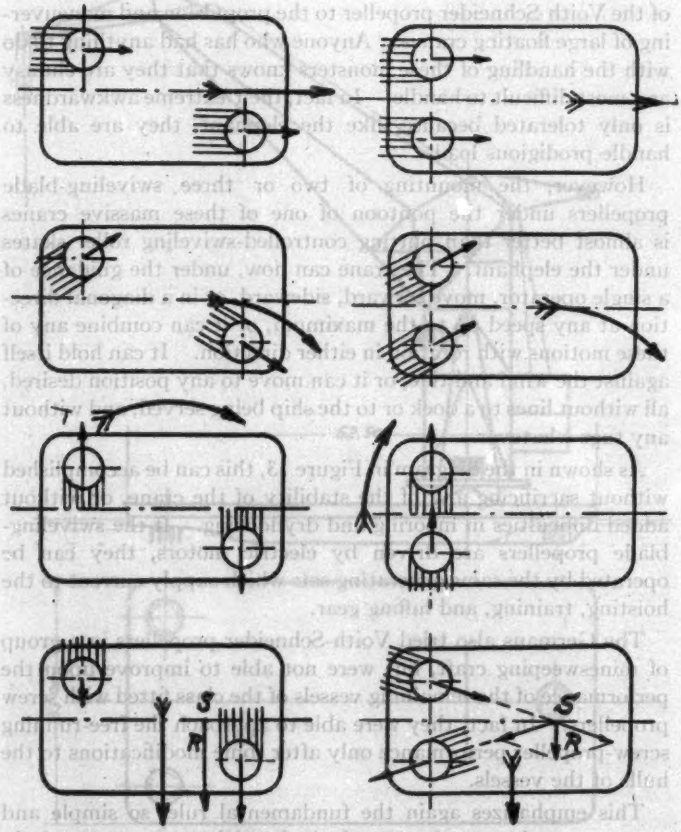
The Germans made a most interesting and useful adaptation of the Voith-Schneider propeller to the propulsion and maneuvering of large floating cranes. Anyone who has had anything to do with the handling of these monsters knows that they are clumsy and most difficult to handle. In fact, their extreme awkwardness is only tolerated because, like the elephant, they are able to handle prodigious loads.

However, the mounting of two or three swiveling-blade propellers under the pontoon of one of these massive cranes is almost better than putting controlled-swiveling roller skates under the elephant. The crane can now, under the guidance of a single operator, move forward, sideward, or in a diagonal direction at any speed up to the maximum, or it can combine any of these motions with rotation in either direction. It can hold itself against the wind and tide, or it can move to any position desired, all without lines to a dock or to the ship being served, and without any tugs whatever.

As shown in the diagram in Figure 13, this can be accomplished without sacrificing any of the stability of the crane, or without added difficulties in mooring and drydocking. If the swiveling-blade propellers are driven by electric motors, they can be operated by the same generating sets which supply current to the hoisting, training, and luffing gear.

The Germans also tried Voith-Schneider propellers in a group of minesweeping craft, but were not able to improve upon the performance of the remaining vessels of the class fitted with screw propellers. In fact, they were able to approach the free-running screw-propeller performance only after some modifications to the hulls of the vessels.

This emphasizes again the fundamental rule, so simple and easy to state but so often overlooked and forgotten, not only in engineering but in all phases of our everyday life. This rule states simply that every separate thing has its particular and singular uses, where it is better than any other thing that can be employed. No thing, however, is universal in its application, nor is it the best for all purposes, whether it is welding, or diesel engines, or vertical-blade propellers.



FIGURES 14a, 14b—MANEUVERING, DIAGRAMS OF CRANE PONTOONS WITH TWO VOITH-SCHNEIDER PROPELLERS.

Corrosion-Resistant Steel Propellers and Propeller Coatings.

Because of a scarcity of copper for manganese bronze the Germans had built during the war a considerable number of ship propellers which were cast in one piece from corrosion-resistant steel. This material possesses greater resistance to erosion than manganese bronze and the other bronzes used for propellers. As the modulus of elasticity of corrosion-resistant steel is about twice that of bronze, the propeller blades bend and deform to a much less degree when in operation under load. This is particularly important in destroyer propellers where the sections are as thin as possible and the unit loadings are very high.

The Germans found that to prevent cracking along the edges of these propellers of cast corrosion-resistant steel they had to make the castings thicker than they would have been if made in manganese bronze. This involved a greater amount of machining and finishing; since the machining costs of corrosion-resistant steel propellers are several times as great as those of bronze propellers, and the machining times are correspondingly longer, the steel propellers were much more difficult and costly to manufacture.

It might have been advantageous, especially in the construction of destroyer propellers, to have used thinner blade sections, which the greater strength and modulus of corrosion-resistant steel would have permitted, but it was found that these thin sections would be subject to vibration in service so that this beneficial feature of the steel could not be utilized.

In the Voith-Schneider propellers referred to in the preceding section, the driving and rotation of each blade is effected through a vertical stock projecting above the blade and made integral with it. For various reasons it was advantageous to have this stock made of steel which would not corrode in the water so that in general the Germans built the blade-stock combination for their cycloidal vertical-blade propellers of corrosion-resistant steel. As the blades of these propellers are of relatively simple form, the machining and finishing problem for blades cast in corrosion-resistant steel presented no serious problem.

At the Escher Wyss Plant in Ravensburg, in southwestern Germany, the author saw special cladding to prevent erosion being applied to the cast-steel blades of Kaplan turbines for

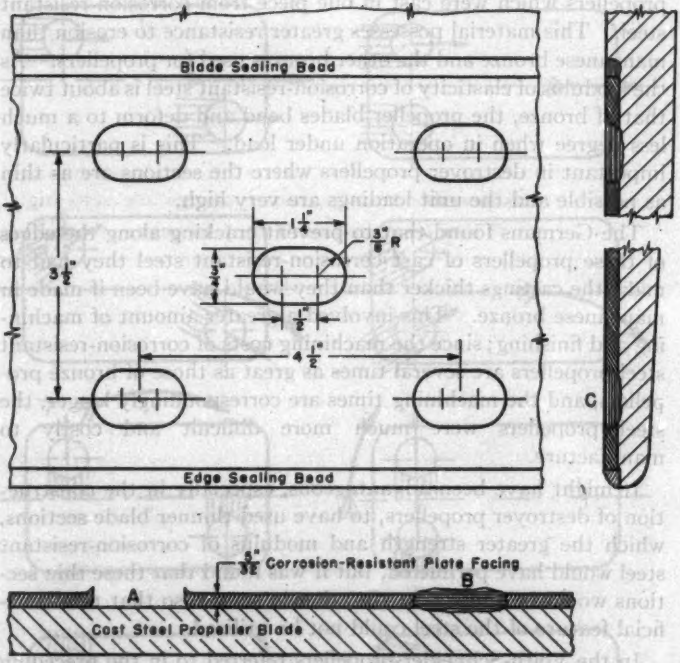


FIGURE 15—DIAGRAM OF EROSION-RESISTANT CLADDING APPLIED TO KAPLAN TYPE PROPELLER BLADES.

The oval holes are punched in the cladding plate, as at "A", and the plate is then laid face down on the prepared steel surface. The plate is held firmly in contact with that surface by numerous clamps around each hole, while the plate and blade are welded together through the hole, as at "B". The plug welds are then ground off to a smooth finish, as at "C", leaving a surface so uniform that the welds cannot be located in it. This sketch was made from memory following the visit to the Escher Wyss Plant at Ravensburg, Germany.

hydroelectric service. A cladding of this material had been applied to similar blades in the United States for many years, but this cladding was in the form of multiple beads of corrosion-resistant steel laid on the cast-steel surface in a very slow and laborious fashion.

At Ravensburg the cladding was in the form of corrosion-resistant steel sheets about 5/32 inch thick, applied to the face of the cast-steel blades by plug welding through large oval holes in the sheet. A sample of the welding rod brought back to the United States and analyzed showed that it was an 18 per cent chromium—8 per cent nickel material; unfortunately it was not possible to obtain a sample of the cladding. The manner of applying the cladding sheets is shown in the diagram, Figure 15.

Mechanical-Mathematical Instruments.

At the establishment of A. Ott, in Kempten, also in southwest Germany, there were many new instruments of the mechanical-mathematical type, such as planimeters, integraphs, and analyzers, developed in recent years by this renowned firm.

The present head of the firm and son of the founder, Doctor Ludwig Ott, displayed with justifiable pride a new harmonic analyzer which might even have surpassed the dreams of Jules Verne, had he been a mathematician or a computer. Instead of selecting one harmonic at a time for an irregular vibration curve, and being capable of picking out all harmonics up to the 9th by as many separate operations, as the Mader analyzer now in use is able to do, this new Ott analyzer is able to select 14 harmonics at a time, and to pick out any selected 14 up to the 33rd harmonic.

Had this truly marvelous instrument been in a research instead of in a manufacturing establishment, it would certainly by now have been reposing in the David Taylor Model Basin, unless of course, it had been seen and appreciated first by some of the other Allied officers who had preceded the author and his party.

Doctor Ott, perhaps known as well among hydraulic engineers for his current meters as among the scientific fraternity of the world for his planimeters, integraphs, and the like, displayed with some pride his current-meter rating basin. Hidden in his basement, it was unknown to the author until the director asked if he wished to see it. Not described in any known American publication, it is likewise not well known to scientists and engineers on this side of the Atlantic.

However, when Doctor Ott spoke of the small residual currents in his small basin, which was only 164 feet long by 4.9 feet wide by 4.9 feet deep, in comparison with the larger currents in larger bodies of water, it was clear that he knew about other model basins in the world and that he understood something of their characteristics. When he said that in his small basin he would have by no means the large residual currents that we would have in the large model basin at Carderock, the author was just on the point of exclaiming, when he restrained himself, how did he know we actually had large residual currents at Carderock?

It was no less startling in a way, to hear the prediction made by Doctor Ott some 4000 miles from Washington, that there would be residual currents in the deep water basin at Carderock from temperature gradients between the water layers. This will be something to look into when life becomes more peaceful again.

It was then reassuring to hear Doctor Ott say that it was the nearness of his basin walls to the current-meter paths that cut down his residual currents, for it had always been suspected that it was the very shallowness and restricted cross section in the old Washington Basin that made that body of water so free of residual currents.

Doctor Ludwig Ott had, incidentally, one of the most unusual offices that the author has ever seen in his many years of visiting. The rather complete technical library stacked on the shelves all about was not too surprising in a place of this kind, the stove was certainly not superfluous, nor was the German woman secretary and all her paraphernalia, not too far from the stove; but it was unusual to find a large drafting table and a drafting machine, a large sheet of drawing paper with a new instrument layout on it, a number of calculating instruments, and a desk about 15 or 20 feet long that was spacious enough to support several activities each for Doctor Ott and his son, who acted as his assistant.

The office, large but not roomy, because of the many things in it, gave the appearance of encompassing all the activities of two able and imaginative scientists except eating and sleeping, as indeed it may well have done. Here the present master and his father before him established and enunciated the policies, supplied the initiative, drive, and direction, governed the finances and public relations, prepared the advertising, and otherwise managed the business. Here the same two, with their own brains and with their own hands, devised and laid out the remarkable

instruments that won a Gold Medal at the World's Columbian Exposition in Chicago in 1893 and that have been among the leaders in this field ever since.

In his production shop Doctor Ott was turning out, at the time of the author's visit, an order of 4000 planimeters of a single size and type for the Russians. It would not be surprising to go back there now and to find him turning out another 4000 of a different size for the same customer.

Regardless of their race and their political affiliations, here in this office several distinguished members of a family dynasty had worked and were working, through wars and tribulations, to achieve a scientific and engineering goal. Not only in the achieving but in the making, their work had to be admired.

The Value of Small Test Facilities.

The trip through Europe did much to impress upon the author the great value of small and simple test facilities in a general scientific program which includes training as well as research, design, and development. To be sure, the United States has no dearth of small-scale test facilities and the potentialities of this type of equipment have certainly not been overlooked in this country. Despite more or less constant association with small facilities of this kind for the past 25 years or more, the author must admit that he came back from Europe with a new appreciation of the great value of simple and not-too-expensive test equipment. He, like so many other Americans of the present day, had been so engrossed with planning and talking of "bigger and better" facilities that he had unconsciously let himself be blinded by their very magnitude. He had let himself drop into the attitude assumed by other Americans who had felt that because something of theirs was the biggest in the world it was by the same token also the best.

Any large research establishment needs a proper balance in its test equipment. A proper balance includes almost everything from the largest to the smallest, and from the simplest to the most complex. For example, the Marine Aircraft Experimental Establishment of the British Ministry of Aircraft Production at Glen Fruin in Scotland had not only the largest air-water entry tank in the world, 150 feet long by 30 feet wide by 40 feet deep, but it had also the smallest transparent-wall tank of any seen in Europe, about 2½ feet square by 6 feet deep. Likewise the

Taylor Model Basin has not only the longest model basin in the world, 2980 feet from end wall to end wall, but probably one of the smallest model basins in existence, only 10 feet long. This tiny basin, in which actual project tests have been made, is like its counterpart complete with tracks and a towing carriage.

In a large progressive country like the United States, there must be available somewhere within its continental limits a set of superlatively large test facilities for investigations in each branch of science, but it is by no means necessary that these large facilities be duplicated at a number of large establishments. This does not mean, of course, that there should not be separate large test facilities, such as those to accommodate airplanes, guided missles, jet engines, rocket engines, rotary engines, and gas turbines, especially where there is so much work in each facility that time cannot be spared for other kinds of work in the same facility. The large or superlatively large test facilities in a large country must, furthermore, always be built by some organization able to finance them. If costs continue to hold their present extremely high level, there will be only one organization in this category, the national government.

At the same time there are vast unexplored possibilities for research to be carried out in small facilities, ranging from somewhat elaborate affairs of intermediate size to homemade varieties of small size. In this respect, the amateur astronomers and youthful radio operators have set a marvelous example of progress and achievement through the medium of apparatus almost invariably built by themselves.

To translate this effort into terms of achievement by European nations during the past decade it may be pointed out as one example that the nose contours for many of the German jet engines for aircraft were developed in a special free-surface-jet water tunnel at the Kaiser Wilhelm Institute für Strömungsforschung at Göttingen, which almost any American university engaged in research work could finance. The V-2 rocket was developed in supersonic wind tunnels which were so flexible and demountable that they could first be moved from Peenemunde on the Baltic to Kochel in Austria and later set up without major repairs at the new Naval Ordnance Laboratory at White Oak, Maryland.

Professor Georg Madelung, Director of the Forschungsanstalt Graf Zeppelin (FGZ) at Stuttgart-Ruit had almost a mania for

building simple and inexpensive pieces of test apparatus which could readily be changed as the circumstances or development of the project required. A few of his simple installations are shown in Figure 16, and there were many more like them in this establishment. In fact, the greater part of the parachute research done in Germany during World War II, which produced such outstanding accomplishments as the ribbon parachute and a new but little-known stabilizing or guiding parachute, was carried out at Stuttgart-Ruit in a group of small wind tunnels built of surplus motors and fans, plywood, sheet metal, and incidental hardware.

Preferred Types of Construction for Test Facilities.

Professor Madelung, in his interviews at the Taylor Model Basin in April and May of 1946, was most emphatic in his opinion that the test facilities and test apparatus designed and constructed for research projects should be so built that they could readily be changed. He made the point that no one could predict at the beginning of a project just what would be wanted in the way of experimental apparatus before the end of it. If the apparatus was so constructed as to be modified easily, then it would be modified from time to time as the research demanded and it would be sufficiently flexible in arrangement to follow the line of research instead of having the line of research restricted by the test apparatus which could not readily be changed.

Professor Madelung, as pointed out previously, made the further point that test facilities of this kind should be simple and relatively inexpensive; in fact, no more expensive than was absolutely necessary to give the immediate results desired and to point the way to the next series of experiments. When it had been determined as a result of successful experiments that certain standardization of design and construction might be established, it was then time, he maintained, to put more money into the test facility and to make it more permanent.

He said that he had been very much provoked by certain authorities (not named by him) who had had the say in the building of the new large transparent wall tank at Stuttgart-Ruit, which was to have been some 115 feet long by 35 feet deep by 20 feet wide. It was his idea (or so he said) that even this large facility should not be too elaborate and expensive because it might in time be found desirable to modify it. Instead, the new tank was being built very solidly and permanently of reinforced

concrete, so much so that sufficient material could not be found for its completion. It had therefore remained in a generally unfinished state throughout most of the year 1944 and all of the year 1945, whereas otherwise it might have been available in a few months, long before the war ended.

These arguments about the design and construction of test facilities are by no means one-sided, notwithstanding that Professor Madelung and his staff made major contributions to the German cause by following his side of the argument. It must be admitted, nevertheless, that the facility which a piece of test equipment may be modified to suit changing conditions in the future is a major feature in its design. It must likewise be admitted that steel occupies a position high on the list of basic materials suitable for building test facilities, and that concrete is a very poor second.

The Role of Personnel in Research.

Though on a trip made primarily to inspect test facilities, the author might have expected that the feature that was to be brought home most forcibly to him was the fact that personnel plays an even more important part than material in experiment and research. The history of scientific progress is replete with stories of achievement by energetic, industrious, and persevering men and women who have struggled along with the crudest and simplest of test equipment. If the full details were known, history would also be found to include fruitless and wasted hours spent by personnel, not adequately trained or not suited by instinct and ability, in making uninspired experiments with elaborate and expensive equipment.

The Germans had both kinds of equipment, varying from the shack, shanty, and barn variety at the Forschungsanstalt Graf Zeppelin (FGZ) at Suttgart-Ruit, to the extremely elaborate and expensive test facilities at the Luftfahrtforschungsanstalt in Völkenrode, near Braunschweig. It may be said for the Germans, however, that almost invariably they used scientists, engineers, technicians, and mechanics who, whether they had streaks of natural genius or not, were admirably schooled and trained in their particular lines of endeavor.

Inquiries in Germany as to the sources of supply of scientific personnel for research establishments brought forth a remarkable similarity in answers, all to the effect that when they could the

Germans made every effort to set up these establishments in the immediate vicinity of a technical institute or university. This gave them not only a continuing supply of young graduates, but made the faculty members available for research and afforded the graduate students an opportunity to work for degrees and to work at the research center at the same time.

The setup at Göttfingen was perhaps one of the best examples. Here the University, the Aerodynamische Versuchsanstalt, and the Kaiser Wilhelm Institute für Strömungsforschung were all in the same city; in fact, they formed more or less the reason for the city. Another excellent example was to be found at Stuttgart, where the Forschungsanstalt Graf Zeppelin was as close to the city as its activities would permit; and where the Director of this Institute was at the same time Professor in Charge of Aeronautical Engineering of the Technische Hochschule in the city. The new Luftfahrtforschung, Munich, was less than 10 miles from that city, with all its institutions of learning and other facilities.

To be sure, when the Germans were forced to disperse their activities because of bombing attacks, these advantages were lost and the work suffered thereby. The construction of large, powerful wind tunnel establishments such as that at Otztal in Austria, which had to be close to available sources of water power, meant virtual isolation of the test and research personnel. This is one of the prices man has to pay for doing new things on a grandiose scale.

The demands for designers and engineers and for mechanics was met in other but no less ingenious ways. In the course of a long visit with staff members of the Askania Werke in Berlin, probably the largest manufacturer and possessor of the most varied line of instruments in the world, it was learned that the men who design their instruments were recruited not from graduates of technical schools and universities, but from their own shop personnel.

Young men who wished to learn the art of *Feinmechanik*, an art which has reached its highest development in Germany, were put through an apprentice training and were then placed in the instrument shops as mechanics. Here they obtained what might be termed the feel of mechanisms, metals, and materials, a sort of intuitive sense which the Askania engineers felt was an essential prerequisite of any designer of instruments and machines. Those who demonstrated aptitude as creative artists in the

building of small machinery, or who felt that they would be good machine designers, were then given leave of absence without pay to go to school to learn the principles of mechanics and to study other subjects necessary for their future work.

When asked whether they paid the school expenses of these young men, the Askania engineers replied emphatically "NO!" If the young men were not willing to use money they had already earned in working at the plant, or to earn money elsewhere for their technical education, Askania felt they did not have sufficient urge to be instrument designers and they did not want them back again, at least not on the engineering staff.

As may be imagined, apprentice schools were no novelty in Germany, but it was unusual, to say the least, to visit the establishment of A. Ott in Kempten, previously mentioned in this article, and to find there a new apprentice school going full blast within seven months of V-E Day.

Doctor Ludwig Ott had lost many of his "fine mechanics" in one way or another but he was busily at work developing another crew with an apprentice school of 35 boys, of ages ranging from 14 to 17. He was using excess war stock in the apprentice shop, which occupied a whole floor in one of his buildings, and he was turning out there a line of cigarette lighters and other small novelties which brought him in an income while his training for a new era of German prosperity was underway.

Looking back upon what he saw in Germany, the author believes that there were no better scientists, engineers, technicians and mechanics in that country than there were in the United States in any selected period of the last decade; but he is firmly of the opinion that the average person in each of these classes in Germany was better trained than his counterpart in this country, and that the Germans definitely had superiority in numbers in each class. From a greater reserve to draw upon they possessed a definite superiority in this respect, which was only prevented from winning a technological war by blunders committed by them along other lines.

One German's Comments on Future Research.

One of the most interesting highlights of the trip was a talk with Doctor Adolph G. Baeumker in an interview sought deliberately to obtain the comments of this prominent member of the

German scientific world on one of the questions listed at the end of the introduction to this article.

Doctor Baeumker had in earlier days been a member, with Doctors Prandtl, Georgii, and Seewald, of the high quadrumvirate which planned and laid out some of the truly remarkable German research organizations and testing establishments; a group which by its united efforts put the German in the forefront with aircraft and in the lead with pilotless aircraft and missiles traveling at supersonic speeds.

Doctor Baeumker, who was living with his family in a small house on the shore of the Wörthsee, west of Munich, had traveled extensively in the United States in 1936, was personally acquainted with most of the outstanding world figures in aeromechanics and aviation, and was himself largely responsible for the conception and layout of the vast aeronautical research plant in operation at Völkenrode and for a second plant which was under construction just south of Munich.

In reply to direct questions as to what he would have been doing had the war continued favorable to Germany and had he been given all the latitude he desired, Doctor Baeumker launched into a long dissertation about long-distance flight in the upper levels of the atmosphere. At the beginning of the visit, he had asked the author's party to speak English to him, so that he could improve his conversation in that language, but he became so earnest and enthusiastic in his comments, and his mind ran so far ahead of his speech, that he unthinkingly lapsed into German time after time.

He pointed out, and rightly so in the author's opinion, that pilotless aircraft and missiles guided from a distance could now fly much farther than they could be guided and navigated. His point was that the real problem of the immediate future was to control ultra-high-speed long-range aircraft so that they could be sent off from one continent and would come down where they were intended to on another continent. These aircraft and missiles, Baeumker went on to say, had to be pilotless because medical scientists were not yet prepared to send pilots and passengers in these craft; they did not know how to protect the human body against the forces, the rarefied atmosphere, and other unusual conditions which they would encounter at great distances above the earth.

Baeumker admitted that an enemy could not be expected to

guide such an aircraft into one of its targets, but speaking for the actual present he said he was ready to drop all other aeronautical research in favor of developing means to shoot pilotless cargo planes across the Atlantic. When he had the navigation problem solved, he would drop it in turn to undertake physiological research to enable the aircraft to carry people as well as inert cargo.

In reply to more specific questions about test facilities which he was known to have designed, Doctor Baeumker said that he would not now duplicate the two very large supersonic tunnels at Völkenrode, with their vertical test sections and circuitous ducts. He would simplify the "pipe work" and would design them with horizontal test sections, as was being done elsewhere.

He also said that in the large "shooting tunnel" for ballistic research at Völkenrode, one of the most unusual test facilities ever designed and built by man but one which for lack of space cannot be described here, he would in addition place the gun mount on a catapult moving at right angles to the line of fire, so as to simulate more nearly the conditions obtaining in guns of fast-moving and faster-maneuvering aircraft.

A whole story by itself could be written of this and other interviews, but the ending would be the same as for this one: What freak of Nature put such brilliance, such fire, and such weird political ideas into the heads of the German people?

Status of German Technical Research on V-E Day.

It may be interesting in conclusion to present a group of three lists which the author prepared and used as a basis for the talks which he gave at the David Taylor Model Basin and at the Bureau of Ships following his return to the United States.

These lists, shown in Figure 17, present the *author's own conclusions* as to the status of reaserch and development in Germany and in the United States on V-E Day. They are admittedly incomplete, they are based on incomplete and often not-too-conclusive evidence, and they represent solely the opinions of one observer. They will, however, summarize his ideas perhaps more forcibly and perhaps more concisely than if he were to endeavor to set down a long and necessarily complicated general story about research and development in Germany during the war just concluded.

The fact that the right-hand list carries a number of items having to do more with production than with research is quite

GERMANY AHEAD of UNITED STATES	NO SUPERIORITY	UNITED STATES AHEAD of GERMANY
SUPERSONIC AIR FLOW	ELECTRONICS	RADAR
GUIDED MISSILES	HIGH SPEED PHOTOGRAPHY	UNDERWATER WEAPONS
ROCKETS	WARSHIP DESIGN	NAVAL AIRCRAFT
SUPER POWER PLANTS	PROPELLERS	AIRCRAFT CARRIERS
HIGH SPEED SUBMARINES	AIR-WATER ENTRY	AUTOMOTIVE VEHICLES
UNDERWATER SOUND GEAR	MINESWEEPING	PRODUCTION METHODS
ACOUSTIC TORPEDOES	UNDERWATER EXPLOSION PHENOMENA	MACHINE TOOLS
PARACHUTES		ATOMIC BOMBS
EXTERIOR BALLISTICS		SEA MINES
SMALL MATHEMATICAL INSTRUMENTS		LARGE MATHEMATICAL INSTRUMENTS
MODEL MANUFACTURE		SHIP STABILIZATION
CAVITATION RESEARCH		MULTI-AXIAL STRESS

FIGURE 17—COMPARISON OF SOME BRANCHES OF RESEARCH AND DEVELOPMENT ON V-E DAY.

Comments concerning the lists here will be found in the text.

intentional. The author is by no means alone in his observation that a great deal of the effort which threw the balance of the war in favor of the United Nations was due to industrial production in the United States and that the Germans probably had a preponderance of scientific effort concentrated on war problems, especially during the years 1943, 1944, and 1945.

Although it was more or less accidental in making up the lists shown in the accompanying figure, the fact that the right-hand and the left-hand lists are of the same length is a simple means of indicating the author's point of view. Briefly this is to the effect that, on V-E Day, neither Germany nor the United States had any definite superiority over the other in the matter of scientific research and technical accomplishments.

ACKNOWLEDGEMENTS.

The author desires to acknowledge his indebtedness to Commander L. A. Rupp, U. S. N., for a careful technical check of this article and Mr. M. C. Roemer, of the David Taylor Model Basin staff, for assistance in editing. Some of the photographs in the article were taken by Lieutenant Commander H. V. Greenough, Jr., U. S. N. R., and by Ensign P. Eisenberg, U. S. N. R., both of whom were members of the U. S. Naval Technical Mission in Europe in 1945. The diagrams illustrating the Voith-Schneider propeller are from an article by Dipl. Ing. G. Franz in the German publication "Hansa" of 22 May 1943.

LET US BUILD THE BEST CANAL AT PANAMA.

By Captain H. H. Little, U. S. N. (Ret.)

One fact we all remember is that Columbus discovered America in an attempt to find a short route to the land of Marco Polo. The early mariners and explorers were frustrated in their search for a route to the far East by the narrow neck of land joining the two continents of North and South America which the Spanish found to be unbroken. The extent of the tie between the continents was not known until Balboa crossed the Isthmus of Panama and gazed upon the Pacific Ocean, at first called "The Southern Sea."

A canal across this Isthmus was the dream of adventurers, promoters, countries and individuals for centuries. Nothing practical was accomplished until 1879 when private French nationals organized the Old Panama Canal Company and started building a "sea-level" canal at Panama. About the same time American financiers commenced operations on a lock canal at Nicaragua. Both efforts failed. Finally, the American Government completed the lock type canal at Panama along the same route which the French had started and we have successfully operated it since it was opened in 1914.

World events have again turned the spotlight on this narrow strip of land. Congress has recently directed a re-study of the means of increasing the capacity and security of the present canal.

World War II taxed the Canal to the utmost. Security during this period became a serious matter. Just as confidence in our ability to protect the Canal was attained, the atomic bomb arrived to haunt the custodians. It is hoped that the hysteria of the atomic bomb discussions will not confuse the real issue of an improved canal.

There are advocates of a re-arrangement of locks.

There are advocates of a "sea-level" canal.

There are advocates of a second canal. The proposed route across the Isthmus at Nicaragua is still a very live issue.

It is evident that the Panama Canal again faces a crisis that will require a most careful investigation of all facts concerning

the functioning of the Panama Canal before arriving at any decision.

Congressional Requirements.

The 79th Congress (1945), 1st Session, enacted Public Law 280, approved December 28, 1945, which authorized and directed AN INVESTIGATION OF THE MEANS OF INCREASING THE CAPACITY AND SECURITY OF THE PANAMA CANAL.

This act indicates that the Congress was fully aware of the limitations of the Canal as observed and reported by the Governor of the Panama Canal from war experience, and that it would be necessary for the Congress to review their previous enactment of Public Law 391, 76th Congress, 1st Session, approved August 11, 1939, which authorized the construction of a third set of locks for the improvement and enlargement of the capacity of the Panama Canal.

1939 Third Locks Project (By-Pass Plan).

Public Law (391) stipulated that the work to be accomplished was to be "substantially in accordance with the plans set forth and recommended in the report of the Governor of the Panama Canal, dated February 24, 1939, and published as House Document No. 210, 76th Congress, 1st Session—at a total cost not to exceed $277,000,000".

The report of the Governor of the Panama Canal provided, in brief, that a third set of parallel locks be constructed at each of the three existing lock locations: Gatun, Pedro Miguel and Miraflores, but located at a distance from them. The new locks were to "be substantially larger than formerly proposed in the 1931 report." The report then asked that "chambers with usable dimensions 1200 feet long and 135 feet wide with 45 feet navigable depth" be provided. The 135 foot width was later increased to 140 feet. This indicates that between 1914 and 1939 recommendations for lock widths have increased from present width of 110 feet through 125, 132, 135, to 140 feet. Again in 1945 the Governor of the Panama Canal indicated that the Secretary of the Navy would recommend a lock width in excess of 140 feet. Recommendations for increased length have remained at 1200 feet while depth increase recommendations have ranged

from 40 to present demand of 45 feet. It is conceivable that lock widths of 175 feet and length of 1500 feet may be needed.

The Governor's 1939 report recommended that the new Gatun lock be a three lift unit located about one-half mile to the east of the present lock structure, that a single lift lock be constructed at Pedro Miguel in a new by-pass channel to be constructed from Miraflores Lake around Cero Paraiso to the west and into Gaillard Cut, and at Miraflores a new double lift lock be constructed in a new channel about one-quarter mile to the west of the present locks, connecting approach from Balboa harbor with Miraflores Lake. Figure 1.

The new locks were conceived to provide the "increased capacity" required, and the separation of the locks from the existing structures, it was thought, would satisfy the "security" demanded.

PUBLIC LAW 280, 79TH CONGRESS.

To understand the intent of Congress, it is necessary to examine in full the enabling language of Public Law 280, quoted in full:

> "Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled, that the Governor of the Panama Canal, under the supervision of the Secretary of War, is hereby authorized and directed to make a *comprehensive review* and *study*, with approximate estimates of costs, of the means for increasing the capacity and security of the Panama Canal to meet future needs of interoceanic commerce and national defense, including re-study of the construction of additional facilities for the Panama Canal authorized by the Act approved August 11, 1939 (53 Stat 1409). He shall also make such study without drafting plans or sketches as he may deem desirable to permit him to determine whether a canal or canals at other locations, including consideration of any new means of transporting ships across land, which may be more useful to meet the future needs of interoceanic commerce or national defense than can the present canal with improvements. He shall report thereon to the Congress, through the Secretary of War and the President not later than December 31, 1947.

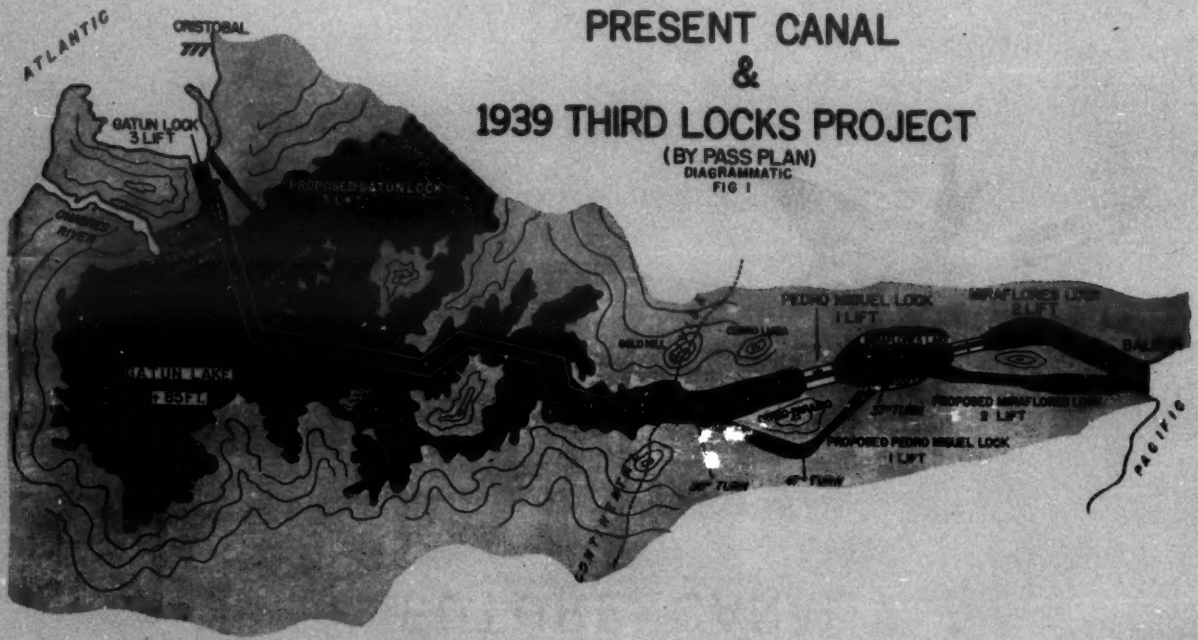

PRESENT CANAL
&
1939 THIRD LOCKS PROJECT
(BY PASS PLAN)
DIAGRAMMATIC
FIG 1
ATLANTIC
CRISTOBAL
GATUN LOCK
3 LIFT
PROPOSED GATUN LOCK
3 LIFT
CHAGRES RIVER
GATUN LAKE
PEDRO MIGUEL LOCK
1 LIFT
MIRAFLORES LOCK
2 LIFT
GOLD HILL
CULEBRA
BALBOA
PROPOSED MIRAFLORES LOCK
2 LIFT
PROPOSED PEDRO MIGUEL LOCK
1 LIFT
PACIFIC

FIGURE 1.

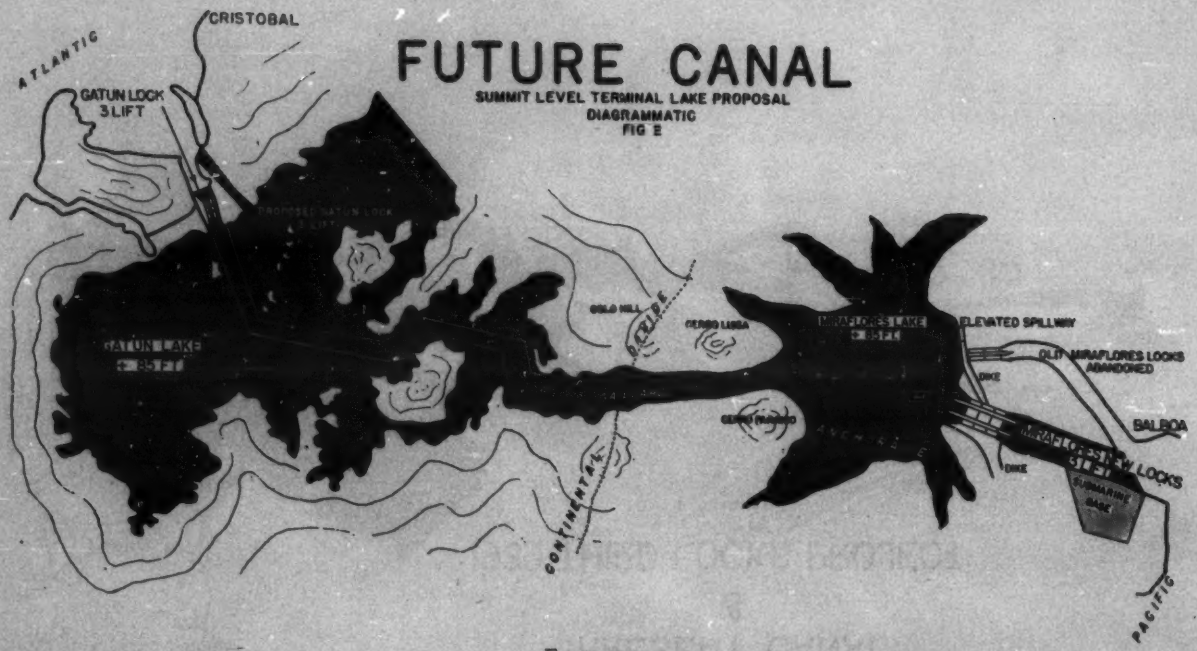
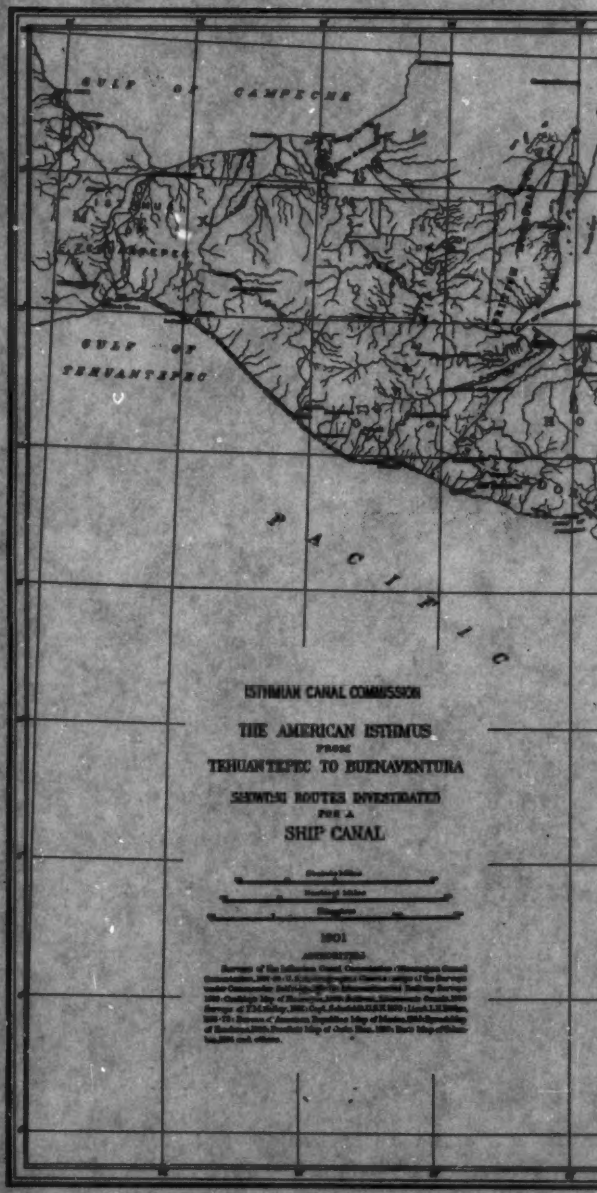

FUTURE CANAL
SUMMIT LEVEL TERMINAL LAKE PROPOSAL
DIAGRAMMATIC
FIG 2
ATLANTIC
CRISTOBAL
GATUN LOCK
3 LIFT
GATUN LAKE
+85 FT
GOLD HILL
CERRO LUCIA
MIRAFLORES LAKE
+85 FT
ELEVATED SPILLWAY
DIKE
OLD MIRAFLORES LOCKS
ABANDONED
BALBOA
DIKE
NEW LOCKS
SUBMARINE
BASE
CONTINENTAL
PACIFIC

FIGURE 2.


GULF OF CAMPECHE
GULF OF TEHUANTEPEC
PACIFIC
ISTHMIAN CANAL COMMISSION
THE AMERICAN ISTHMUS
FROM
TEHUANTEPEC TO BUENAVENTURA
SHEWING ROUTES INVESTIGATED
FOR A
SHIP CANAL
1901

JAMAICA
GULF
HONDURAS
MOSQUITO
GULF
PANAMA

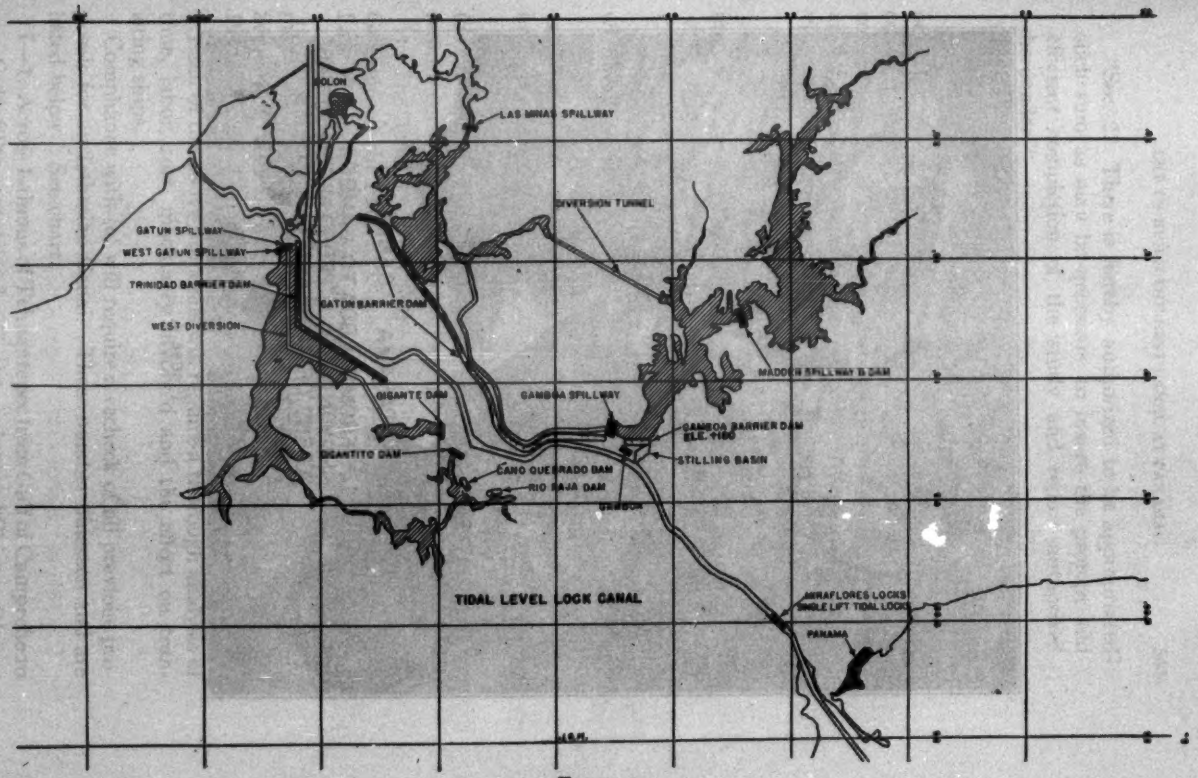

COLON
LAS MINAS SPILLWAY
DIVERSION TUNNEL
GATUN SPILLWAY
WEST GATUN SPILLWAY
TRINIDAD BARRIER DAM
GATUN BARRIER DAM
WEST DIVERSION
MADDEN SPILLWAY & DAM
GIGANTE DAM
GAMBOA SPILLWAY
GAMBOA BARRIER DAM
ELE. +100
GIGANTITO DAM
STILLING BASIN
CANO QUEBRADO DAM
RIO BAJA DAM
TIDAL LEVEL LOCK CANAL
MIRAFLORES LOCKS
SINGLE LIFT TIDAL LOCKS
PANAMA

FIGURE 3.

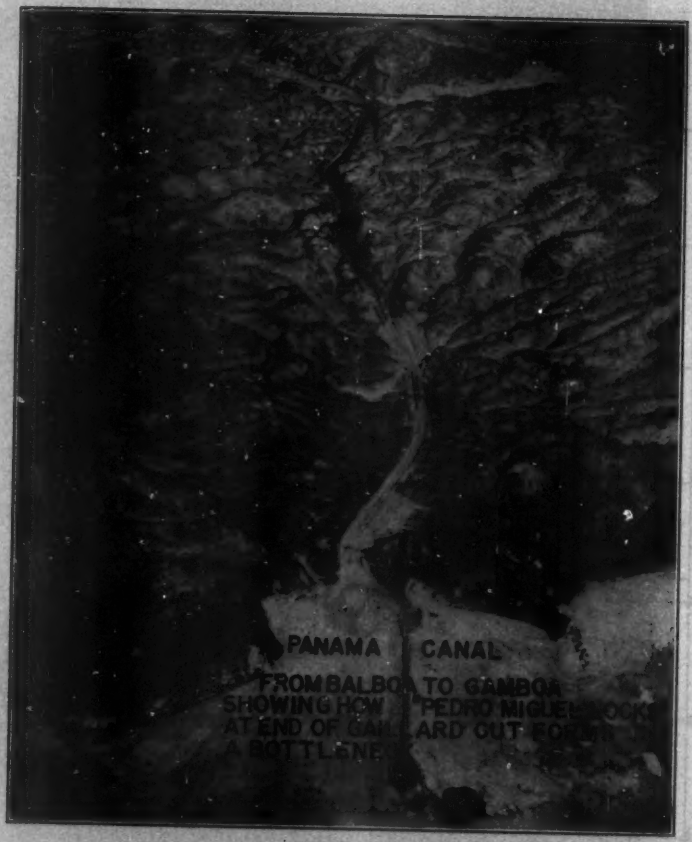

PANAMA CANAL
FROM BALBOA TO GAMBOA
SHOWING HOW
AT END OF
A BOTTLENE

FIGURE 4.

"Sec. 2. There is hereby authorized to be appropriated such sum as may be necessary to insure the prompt and efficient completion of the study and report authorized hereunder."

REQUIREMENTS OF PUBLIC LAW 280.

The enabling act thus reopens the entire subject of an interoceanic canal. In view of the many canal proposals and the conflicting views of various groups as to the canal needs of ocean commerce, the study contemplated will provide ship operators and their allied interests an opportunity to make known their views as to the improvements needed to best serve all shipping.

The act requires:

(a) A comprehensive *review* and study of the means for increasing capacity and security of the Panama Canal.

(b) *Restudy* of the construction of additional facilities for the Panama Canal, authorized by the act approved August 11, 1939.

(c) Such study as will permit the Governor to determine whether a canal or canals at other locations may be made useful.

(d) Any *new* means of transporting ships across land which may be more useful than the existing canal with or without improvements.

In order to comply with (a) and (b) above, existing proposals for the improvement of the Panama Canal as it now exists will require consideration of the following:

1. The THIRD LOCKS By-Pass Plan recommended by the Governor of the Panama Canal in 1939 and authorized by Public Law 391, 76th Congress, approved August 11, 1939.

2. The SUMMIT LEVEL TERMINAL LAKE proposal submitted by Captain Miles P. DuVal, U. S. N. before the Panama Section of the American Society of Civil Engineers on May 20, 1943. Figure 2.

Each of the above proposals will require a thorough analysis of time, labor, cost, machinery involved and the effect on transiting ships.

Compliance with (c) will require a recheck of all previous proposals for an Isthmian Canal. These number nineteen and are listed below. See chart.

I—1. Across Isthmus of Tehuantepec from Gulf of Campeche to Gulf of Tehuantepec using Coatzacoalcos and Chicapa Rivers.

II—2. Across Honduras from Bay of Honduras to Bay of Fonseca.

III—3. Across Isthmus at Nicaragua using San Juan and San Carlos Rivers to the Gulf of Nicoya.

4. Across Isthmus at Nicaragua using San Juan River, Lake Nicaragua, Rio Nino, Tempisque River to Gulf of Nicoya.

5. Across Isthmus at Nicaragua using San Juan River, Lake Nicaragua, Sapoa River to Salinas Bay.

6. Across Isthmus at Nicaragua using San Juan River, Lake Nicaragua with outlet at San Juan del Sur.

7. Across Isthmus at Nicaragua using San Juan River, Lake Nicaragua with outlet at Brito.

8. Across Isthmus at Nicaragua using San Juan River, Lake Nicaragua, Lake Managua, Tamarinda River to the Pacific Ocean.

9. Across Isthmus at Nicaragua using San Juan River, Lake Nicaragua, Lake Managua, to Port Realejo.

10. Across Isthmus at Nicaragua using San Juan River, Lake Nicaragua, Lake Managua to Bay of Fonseca.

IV—11. Across Panama using River Chagres via Gorgona River to Bay of Panama (Present Canal).

12. Across Panama using Chagres and Trinidad Rivers to Caimito on Bay of Panama.

13. Across Panama from Limon Bay using Chagres, Bonito and Bernado Rivers to Bay of Panama.

14. Across Panama from Gulf of San Blas using Chepo River to Bay of Panama.

V—15. Across Isthmus of Darien from Caledonia Bay to Gulf of San Miguel.

16. Across Isthmus of Darien using Arguia, Paya and Tuyra Rivers to Gulf of San Miguel.

17. Across Isthmus of Darien using Atrato and Nipipe Rivers to Cupica Bay.

18. Across Isthmus of Darien using Atrato and Truando Rivers to Kelley's Inlet.

19. Across Isthmus of Darien from Gulf of Uraba using Atrato and Tuyra Rivers to Gulf of San Miguel.

Most of the routes listed above can be dismissed as feasible canal routes with brief comment based upon surveys held in times passed. However, certain other routes such as across Lake

Nicaragua must be sufficiently studied so that an up-to-date analysis will be available to record for all time the operating advantages and disadvantages of that route as compared to the Panama Canal. The last study of the Nicaragua Canal route, completed in 1931, dealt almost exclusively with engineering features.

Paragraph (d) would imply that a "sea-level" canal or a "Straits of Panama" was in mind. Such a proposal was recently sponsored for Panama by Mr. John G. Claybourn, Superintendent of the Dredging Division of the Panama Canal before the Annual Convention of the American Society of Civil Engineers, held in New York City on January 16, 1946. In this work Mr. Claybourn was supported by Brig. Gen. Hans Kramer, U. S. A., Retd., Consultant to the Governor of the Panama Canal for Sea Level Studies. Figure 3.

A Sea Level Canal.

As the narrowest stretch of the American Isthmus is not at Panama, it would appear justifiable, in compliance with (d) and in the pursuit for "security", that some other locations for a sea level or tidal level canal such as (15) above (Caledonia Bay to Gulf of San Miguel) or one of the routes from the Gulf of Darien be studied. With the great advance in aerial photography it is now possible to produce terrain maps of rubber as were used so successfully in World War II, showing the exact configuration of the land at all previously proposed crossings. These maps would greatly simplify study and discussions which could be conducted in a conference room rather than "on site."

A sea level canal using a tidal lock could not greatly increase the capacity due to very moderate speed that vessels would have to make throughout the entire distance of transit. To convert to sea level and keep the Canal operating while excavation work is in progress would tax the ingenuity of construction engineers. No machinery now exists which could accomplish this type of dredging. To handle the flood waters of the area without a "Gatun Lake" would be a major engineering undertaking which has not been solved.

Security features for a "sea level" canal certainly would be no better than for the lock canal. The possibilities of blocking or flooding would be as great a hazard as damage to a lock, spillway or dam.

Shouldn't the possibilities of another canal at an entirely new location be considered at this time rather than a scheme which might jeopardize the Canal we now have?

We have a good usable Canal which has been operating successfully for over thirty years. It has a definite limitation in capacity which can be approximately determined and it has operational defects. We have solved control of the flood waters. We have learned to control the slides. The cost of converting it to "sea level" would be enormous. The slides and the disaster which might overwhelm the effort to convert to "sea level" might destroy all the expenditures and accomplish nothing. An aceeptable plan for a "sea level" canal has not been made. Any plan for a "sea level" canal is still in the dream stage.

The issue is clear. The present Canal requires improvement. That must be done before there can be any conversion of the present Canal. There are many known operating problems. These require solution. Some attention must be paid to the experience gained by the users of the Canal.

"Straits of Panama."

Throughout the thirty years since a passage across the Isthmus was opened to ocean commerce on August 15, 1914, the Canal has performed effectively the task of transporting ships.

All early proposals for a canal had contemplated a sea level "Straits of Panama." The present vast amount of world scientific knowledge, accumulated by recent colossal engineering accomplishments, was not known when the thoughts of a canal were first reduced to concrete proposals.

The early "hydrographers" were not aware of the exact difference in tidal range between the two oceans. Geologists were not informed of the delicate balance of the crumbled piles of matter which are the Earth's crust and, to us, just hills and mountains. The possibilities of serious slides caused by upsetting balance by mechanical excavations were not visualized. Some geologists have asserted that deepening the Canal to sea-level would stir new slides areas, starting huge masses of rock and earth on the move.[1]

The inspired and capable French engineers who were the first to actually attempt the building of a canal across the Isthmus, had a "sea level" canal for their objective. Without the aid of

[1] Christian Science Monitor of June 26, 1946.

modern earth moving machinery, these brave men actually excavated 78,150,000 cubic yards of earth and stone,[2] in operations which extended across the Isthmus through Culebra Cut from the Atlantic to the Pacific, traversing substantially the route finally adopted by the American builders. Of the total French excavation, 29,908,000 cubic yards were useful to the American construction.

The opening of the Canal has had a profound influence on the lives of the people of the world. Opened immediately preceding World War I, it permitted urgently needed men and materials to move quickly, with increased security, from one part of the world to the other. Combatant vessels used the Canal as a by-pass to reach enemy forces quickly. With the advent of the Canal, trade routes to all parts of the world were redrawn. During World War II, war vessels moved to the Pacific at a time when this country's freedom hung in the balance.

Canal Limitations.

During these thrity or more years the Canal has performed the functions envisioned by the builders.

Little did they realize in the beginning that the dimensions established for the lock chambers would limit the beam and length and draft of ships for years to come. Yet during this period the Canal lock width was the controlling factor in large ship construction. It was not until 1935 that these limits were exceeded. In that year a ship was constructed with a beam in excess of the lock chamber width. This ship, the *Normandie*, was given a beam of 117.9′ and length of 1029′. She was designed entirely for the fast Trans-Atlantic service. The British countered the attempt of the French to capture the cream of Trans-Atlantic trade with the *Queen Mary* built in 1936 and measuring 118.6′ x 1019′, and the *Queen Elizabeth* 119′ x 1031′ in 1940. Lengths are overall.

The advent of the aircraft carrier with its wide and long landing platform, the large battleship with bulging "blisters" for torpedo protection, required a beam greatly in excess of the 110′ limiting width of the Canal locks. This ship construction was accepted notwithstanding the handicap introduced thereby of the long voyage through the Straits of Magellan in order to pass from one ocean to the other.

[2] Ralph Z. Kirkpatrick, Reference Book on Panama Canal, p. 37.

Canal Problems.

During the many years of canal operations, the organizations charged with maintenance and operation of the Canal have done a masterful job. There have been many problems.

Slides.

The repeated slides of material, which came to be known as "cucaracha" from the name of the village near which the largest slides occurred, has constantly plagued the Canal engineers. These slides had the slow and irresistible movement of the volcanic flow of molten lava.

The Star and Herald of Panama stated on February 6, 1944, "The cucaracha formation was one of the most troublesome during the construction of the Canal and millions of tons of material were cascaded into the Canal prism both before and after it was opened. The formation consists of soft semi-plastic to plastic claylike material with inter-bedded indurated beds and hard conglomerate. The formation, as a whole, is highly susceptible to sliding, particularly when saturated. Dredges were employed in Gaillard Cut repeatedly to keep the passage open to navigation. In all this time the Canal suspended traffic for less than 260 days. The largest single period of suspension of traffic because of slides was 216 days.

Water Control.

The frequency of heavy rainfalls of flood-proportions taxed the ingenuity but proved the resourcefulness of the engineers in charge. Slides and floods became the major maintenance problems of the Canal engineers.

Another serious problem with which the Canal engineers were faced was the supply of water required to support the ever increasing number of lockages.

The impounded waters of Gatun Lake had served the Canal effectively. Several years of reduced rainfall indicated a problem almost as serious as the floods caused by an excess of water. As these two problems were so closely related it became apparent that the solution was additional water storage and the impounding and control of such water.

The French had originally visualized the need for flood control by means of a dam and storage basin in the upper Chagres at Alhajuela. The flood of 1909 demonstrated the urgent need for

additional flood control. The Secretary of War, at that time, with a board of engineers, made a survey and, convinced that additional water would be required for future operation, recommended that a grant of additional water shed of the upper Chagres be obtained from the Republic of Panama and that a dam be constructed to impound and control these waters.

MADDEN DAM.

The grant was obtained but it was not until 1930 that funds were appropriated to undertake the project. The Congressional Act stipulated that the dam be named "Madden" in honor of Congressman Martin Madden who as chairman of the House Committee on Appropriations had contributed so much to the construction of the Panama Canal. The project was started in 1931 and completed in 1935.

Having solved the problem of sufficient water stowage to handle the maximum number of vessels which could be passed through the Canal during the period of maximum water shortage, Canal engineers turned their attention to other problems and possible improvements. Unfortunately much of the past discussion of Canal improvement ignored the operating problems.

Except for increase of water storage by erection of the Madden dam, no major changes have taken place on the Canal since it was opened in 1914.

MAINTENANCE PROJECTS.

It is true that harbors have been dredged, docks have been built, channels have been widened, curves have been improved, slides into the Canal have been removed, hills have been lowered, the railroad has been relocated many times, defense installations have been improved, a highway for motor traffic has been built, dams have been strengthened, but no fundamental modifications or improvements in the Canal have been undertaken since it was placed in operation.

ENGINEERING PROBLEMS.

The emphasis has been on engineering problems such as foundations for new locks, size of chambers, location of construction, availability of material, type of operating machinery. None of these will eliminate the hazard of surges back and forth in the Gaillard Cut, the rush of flood waters into the Canal from swollen

streams; the narrow passages, sharp curves, crosswinds and fogs; and above all the absence of a summit level anchorage basin on the Pacific.

Early Studies.

At the present time, in the study for the modernization of the Canal, it is interesting to repeat the words of a Senate resolution dated March 19, 1866, requesting the Secretary of the Navy to report on "various proposed lines of interoceanic canals and railroads between waters of the Atlantic and Pacific Oceans." The resolution stated:

> "It is the aim of the Honorable Senator, Mr. Conness, of California, to acquire by the answers to his resolution such accurate knowledge with regard to the whole question as will, in the first place, prevent re-examination of any ground which is already sufficiently known, and in the second place, will prevent any useless expenditure of money upon schemes that are infeasible or unpromising."[1]

It is obvious now that with the limited scientific knowledge available at the time of this resolution that surveys made at that time would be useless for present day consideration.

Present day studies should have in mind the ultimate demands on the present plant. At what future date will the maximum number of lockages, with the computed volume of water available, be demanded?

What will be the maximum size of the future "largest" ship?

How many additional sets of locks can effectively be used?

Answers to these questions will point out the limiting factors for the present Canal from an operating point of view.

It is evident that the Canal will have a limit in the number of ships which can be passed through in any twenty-four hours. This limit will depend upon the amount of available summit level water and the speed of lock operation.

A further study based upon annual increase in tonnage transited should indicate the approximate date at which the Canal will be operating at full capacity.

The present Canal with double barrel locks can operate a maximum of 54 lockages per day. During lock overhaul periods, the

[1] S. Ex Doc. No. 62 (39th Congress, 1st Session).

capacity of the locks is 27 lockages per day.[3] During fog periods in Gaillard Cut, these capacities are reduced.

It is estimated that with the installation of a third set of locks the capacity can be increased to 82 lockages per day maximum.

During the year 1930, 30,000,000 net tons of shipping were locked through the Canal. At that time tonnage was increasing at the rate of 1,000,000 tons per year. From 1930 to 1940 tonnage transited held steady at about 30,000,000 tons. During World War II the rate again rapidly increased. With such figures in mind, some approach can be made to the time when even a modernized Canal will have reached its limit of capacity.

Operating Problems.

The experience of mariners who have used the Canal for many years, has revealed serious marine operating problems which must be solved. Each ship captain approaching the Canal knows that he is facing a period of worry and tension. He thinks of the "bottle-neck" at Pedro Miguel where the timing must be scheduled to the second. He recalls the frequent night fog in Gaillard Cut. The delay caused by double handling at the two Pacific locks will annoy him. They constitute an operating problem. He is aware of the many accidents which have overtaken other ships in making the passage. He has heard about lockage surges in Gaillard Cut and knows of the sinking of ships in the Cut. He knows of collisions with other ships in the narrow portions of the Canal and with the locks. If he is unfortunate enough to have such an accident he also knows that his ship will be delayed either at the Canal or on reaching his destination while repairs are effected. Figure 4.

The causes of accidents are not too well known, but some of them can be eliminated by the removal of causes which will be revealed by a full study and discussion of the operating problems.

It is natural for the uninformed to consider a "sea level" canal as the most desirable type. They imagine a wide strait across the Isthmus. They do not realize the great amount of earth to be moved, the slides to combat or the flood waters to be controlled. Passing an ocean going ship through a long, narrow, twisting gorge with uncontrolled currents and surges isn't the simple problem the uninitiated visualize.

[3] Report of Governor Panama Canal, August 4, 1931, Ho. Doc. #39 (72nd Congress) 1st Session, p. 25.

A New Canal Commission.

The problems of modernization of the Panama Canal are vast. The time has come when changes for the Canal should be discussed on the same scale as was the original project of building it. Shipping interests are directly concerned. Marine insurance companies have a great interest. The Navy has a stake of paramount proportions. Congress which authorizes the expenditures and the people who pay the bill should know all the factors before authorizing the expenditure of their money. The United States as the sole custodian of this great waterway has international obligations to fulfill.

The problem is too great for any one man to solve. The responsibility is too great for any one man to shoulder. No single agency should dominate the decision as to the future Canal. Only an objective study of the operating problems by the best qualified engineers and operating men representing all the agencies involved can arrive at a sound plan.

Public Law 280 indicates that the Panama Canal is facing another crisis in its history. This law offers a great opportunity to obtain the data upon which to base a decision the Country can accept.

In line with precedent during previous crises in Canal history, the best way to arrive at a proper solution is by the appointment of a special Isthmian Canal Commission, composed of the ablest engineers and Marine operating men in the country, to delve into the subject and arrive at the best plan.

THE MEASUREMENT OF GAS TEMPERATURE.

By G. F. Hubing, Lieutenant D(L), U. S. N. R.

To the designers of power plants, heating systems, drying equipment and industrial furnaces and to the personnel charged with the successful operation of such installations, a knowledge of the actual temperature of air circulating throughout the system is of vital importance, for upon the control of these temperatures may depend the success of the entire plant. It is almost universal practice to place a thermocouple or thermometer into a duct or exhaust stack and to accept without further investigation any indication of air temperature so obtained. In many cases such a practice is satisfactory from the standpoint of day to day operation where it is desired to maintain conditions over a period of time. The operator of a continuous ceramic kiln burning sanitary ware would be less interested in knowing actual temperatures of the circulating air than he would be in maintaining some arbitrary indication on his instruments, which (he knows) if maintained, will produce a properly fired product. On the other hand, an engineer charged with the operation of an installation processing a certain chemical product might be vitally interested in actual air temperatures, not only because of the influence of temperature on reaction rates but to preclude the danger of thermal decomposition, fire, explosion, etc.

It is well known among engineers that factors other than pyrometer indications should be considered when determining gas temperatures. What, however, are these factors and in what way should they be considered? In an attempt to answer this question the following is presented. Most of the text, having been developed for personal use, has been collected at odd times over a period of several years and contains data taken at random from standard publications and tables and from the personal notes of friends and co-workers of the writer. The experimental data is the result of repeated observation and tests of laboratory and industrial installations.

Transfer of heat from one body to another at a lower temperature is accomplished by conduction and/or radiation. A third method of transfer, however, is often of more importance; that is,

"sweeping", whereby a body of gas is caused to move along the surface of a liquid or solid body such as the inside of a duct or exterior of a furnace wall. The heat exchange by conduction between a solid body and the particles of a gas, even though the gas be originally at rest, will produce a movement of the gas particles, the effect of which from the standpoint of heat transfer is far more important than conduction alone. As this condition is invariably encountered in practice we are interested in the heat transfer resulting from two actions, namely sweeping and radiation, and the discussion will be confined to that of determining the relationship between actual air temperature and pyrometer indication in a duct passing heated air when these two methods of heat transfer are in action. Figure 1 represents a round duct with pyrometer inserted and is self explanatory.

An expression proposed by Nusselt gives

$$\beta_1 = .0362\,[\lambda^{.214} \times (\nu g c)^{.786} \times d^{-.16} \times l^{-.054}] \qquad (A)$$

where

β_1 = coefficient of sweeping
λ = coefficient of conduction
ν = velocity of gas flow—meters per hour
g = specific weight of the gas
c = true specific heat of the gas
d = diameter of duct passing the gas—meters
l = length of duct passing the gas—meters

Values of λ for some common material are given in Table I.

TABLE I

Material	λ — Kg. Cal./M²/Hr./°C.
Copper	320.
Aluminum	175.
Low Carbon Steel	56.
Graphite	4.2
Silica Brick	.96 + .0004 (t)
Concrete	.7 to 1.2
Common Brickwork	.35
Wood (Dry)	.30
Sand (Dry)	.05

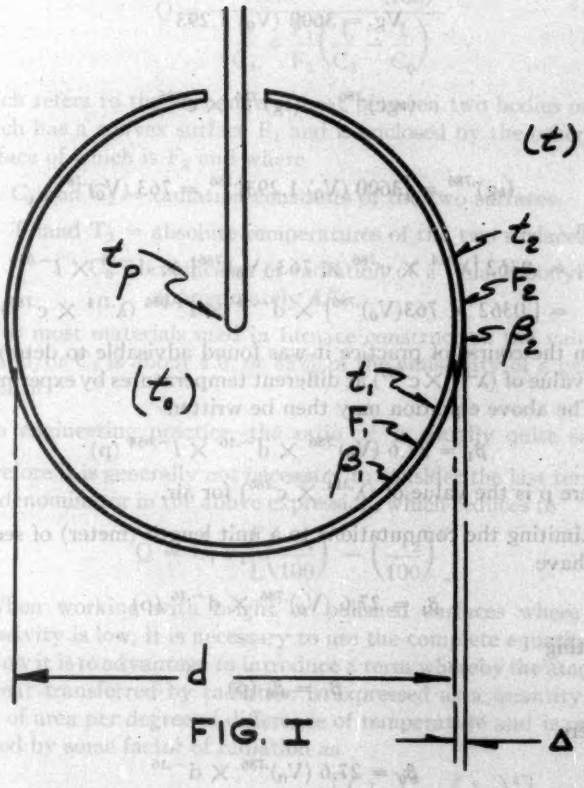


FIG. I

If we let V_0 represent the velocity of the gas in meters per second when its temperature is at 0°C. we get, for atmospheric air

$$V = 3600\ (V_0)$$

and

$$Vg = 3600\ (V_0)\ 1.293$$

Let

$$(\nu gc)^{.786} = (\nu g)^{.786} \times c^{.786}$$

and

$$(\nu g)^{.786} = [3600\ (V_0)\ 1.293]^{.786} = 763\ (V_0)^{.786}$$

then

$$\beta_1 = .0362\ [\lambda^{.214} \times c^{.786} \times 763\ (V_0)^{.786}] \times d^{-.16} \times l^{-.054}$$

$$= [.0362 \times 763(V_0)^{.786}] \times d^{-.16} \times l^{-.054}\ (\lambda^{.214} \times c^{.786}) \quad (B)$$

In the course of practice it was found advisable to determine the value of $(\lambda^{.214} \times c^{.786})$ at different temperatures by experiment.

The above equation may then be written

$$\beta_1 = 27.6\ (V_0)^{.786} \times d^{-.16} \times l^{-.054}\ (p) \quad (C)$$

where p is the value of $(\lambda^{.214} \times c^{.786})$ for air.

Limiting the computations to a unit length (meter) of section we have

$$\beta_1 = 27.6\ (V_0)^{.786} \times d^{-.16}\ (p) \quad (D)$$

Letting

$$\beta_1 = \beta_0\ (p)$$

where

$$\beta_0 = 27.6\ (V_0)^{.786} \times d^{-.16} \quad (E)$$

we compute β_0 for several values of V_0 and d[1] and plot. The result is given in Plate I. Values of p plotted against temperature are given in Plate II.

[1] If the duct is of a cross section other than circular, then

$$d = \frac{4}{p}(a)$$

Where a is the cross section area in square meters and p the perimeter in meters.

Stefan's Law

$$Q = CFT^4$$

has been expanded by Bolmann, Kirchhof and others to

$$Q = \frac{F_1\left(\frac{T_1}{100}\right)^4 - F_1\left(\frac{T_2}{100}\right)^4}{\frac{1}{C_1} + \frac{F_1}{F_2}\left(\frac{1}{C_2} - \frac{1}{C_0}\right)} \qquad (F)$$

which refers to the exchange of heat between two bodies one of which has a convex surface F_1 and is enclosed by the other, the surface of which is F_2 and where

C_1 and C_2 = radiation constants of the two surfaces

T_1 and T_2 = absolute temperatures of the two surfaces

C_0 = coefficient of radiation of a "black body", approximately 4.7

For most materials used in furnace construction the value of C_1 and/or C_2 is about 4.0, or 85% of the emissivity of a perfect radiator.

In engineering practice, the ratio $\frac{F_1}{F_2}$ is usually quite small, therefore it is generally not necessary to consider the last term of the denominator in the above expression, which reduces to

$$Q = C_1 F_1\left[\left(\frac{T_1}{100}\right)^4 - \left(\frac{T_2}{100}\right)^4\right] \qquad (G)$$

When working with bright or polished surfaces where the emissivity is low, it is necessary to use the complete equation.

Now it is to advantage to introduce a term whereby the amount of heat transferred by radiation is expressed as a quantity per unit of area per degree of difference of temperature and is represented by some factor of radiation as

$$R = \frac{Q}{F_1(t_p - t_1)} = \frac{C_1 F_1\left[\left(\frac{t_p}{100}\right)^4 - \left(\frac{t_1}{100}\right)^4\right]}{F_1(t_p - t_1)} = \frac{C_1\left[\left(\frac{t_p}{100}\right)^4 - \left(\frac{t_1}{100}\right)^4\right]}{(t_p - t_1)} \qquad (H)$$

For convenience in tabulating values of R, a mean temperature t_m is inserted midway between t_1 and t_2. We then plot values of R against values of t_m as in Plate III.

The reader may question the soundness of the development where R is referred to a mean temperature t_m rather than to the actual temperatures of the radiating surfaces. It has been found in practice that where one comparatively small body is surrounded by another and larger body (as in the case of a thermocouple inserted into an exhaust stack or air duct), the temperature difference between the two surfaces ($t_p - t_1$) is usually not greater than about 200°C. This is especially true after "equilibrium"[2] has been reached. The values of R given in Plate III have been computed on this assumption and tests in the laboratory and on industrial equipment indicate they may be used with confidence.

If the surrounding atmosphere is at a temperature of 20° C, the heat transfer due to convection from a duct, furnace wall etc., can generally be fixed at approximately 3.73 kilogram calories per hour per square meter per degree of temperature (above absolute) of the exposed surface. If the temperature of the exposed surface (t_2) is s degrees above the temperature of the surroundings, then

$t_2 = (293 + s)°$ K. = wall temperature

$t = 293°$ K. = temperature of surroundings

and the amount of heat transferred by radiation is, from equation (G),

$$q = C_1\left[\left(\frac{t_2}{100}\right)^4 - \left(\frac{t}{100}\right)^4\right]$$

Letting $C_1 = 4.0$ and combining the expressions for convection and radiation, the total heat transferred per hour per square meter of area is

$$\alpha = 3.73\,(s) + q = 3.73\,(s) + 4.0\left[\left(\frac{293 + s}{100}\right)^4 - \left(\frac{293}{100}\right)^4\right] \quad (I)$$

[2] Thermodynamically, "temperature" presumes a thermal equilibrium. In almost all practical cases, however, this very condition is not fulfilled. On the contrary, it is usually a case of non-static, or "transflux" equilibrium. It will be realized that in the case in which we are interested, namely one of transflux equilibrium, we are concerned with the maintenance of a flow of energy, whereas in the case of true equilibrium the flow of energy per unit of time through any unit plane is equal to zero. It is evident that if we deal with true equilibrium the system is well defined by thermodynamic values which are independent of the nature of the substance, while in the case of transflux equilibrium we require for our temperature calculations the value of certain physical constants such as heat conductivity, degree of molecular dissociation, emissivity, effective cross section, etc.

where α is expressed in kilogram calories per square meter per hour. From this relationship, the data given in Plate IV is calculated. It stands then, that the amount of heat transferred per degree of temperature difference between the wall and the surroundings is

$$\beta_2 = \left(\frac{\alpha}{s}\right)$$

Let us assume that we have a circular duct constructed of low carbon steel ($\lambda = 56$), inside diameter of .30 meter, wall thickness .0025 meter, passing air at 500°C. with a velocity of 9.4 meters per second. What would be the reading of a pyrometer if placed in the air stream?

Reducing the velocity to what it would be at 0°C. we have

$$V_0 = \left(\frac{273}{500 + 273}\right) 9.4 = 3.32 \text{ meters per second}$$

From Plate I we get $\beta_0 = 85.81$ and from Plate II we get $p = .165$, therefore

$$\beta_1 = \beta_0 (p) = 14.16$$

Values of t_1 and t_2 are now assumed. From the very dimensions of the duct it can be concluded that due to the thin wall, the difference between t_1 and t_2 will be small. This being the case, let $t_1 = 253°C.$ and $t_2 = 252°C.$ Now $t_2 = 252° = (20° + s)$, therefore $s = 232°C.$ From Plate IV or equation (I) we get

$$\alpha = 3.73\ (232) + 4.0\left[\left(\frac{525}{100}\right)^4 - \left(\frac{293}{100}\right)^4\right] = 3610$$

thus

$$\beta_2 = \left(\frac{\alpha}{s}\right) = \left(\frac{3610}{232}\right) = 15.55$$

The total quantity of heat transmitted from the hot gas at t_0 through the wall of the duct and to the surroundings at t is

$$Q_T = \frac{(t_0 - t_1)}{\left(\frac{1}{F_1\ \beta_1}\right)} = \frac{(t_1 - t_2)}{\left(\frac{\Delta}{\lambda M}\right)} = \frac{(t_2 - t)}{\left(\frac{1}{F_2\ \beta_2}\right)}$$

$$= \frac{(t_0 - t)}{\left(\frac{1}{F_1\ \beta_1}\right) + \left(\frac{\Delta}{\lambda M}\right) + \left(\frac{1}{F_2\ \beta_2}\right)}$$

or in this case

$$Q_T = \frac{(500 - t_1)}{\left(\frac{1}{.30\ (14.16)\ \pi}\right)} = \frac{(t_1 - t_2)}{\left(\frac{.00025}{56\ (.3025)\ \pi}\right)} = \frac{(t_2 - 20)}{\left(\frac{1}{.305\ (15.55)\ \pi}\right)}$$

$$= \frac{(500 - 20)}{\left(\frac{1}{.30\ (14.16)\ \pi}\right) + \left(\frac{.00025}{56\ (.3025)\ \pi}\right) + \left(\frac{1}{.305\ (15.55)\ \pi}\right)}$$

$$Q_T = \frac{(500 - t_1)}{(.07473)} = \frac{(t_1 - t_2)}{(.000047)} = \frac{(t_2 - 20)}{(.0672)} = \frac{(480)}{(.1419)} = 3382$$

Using the first and third expression of this equation and solving for t_1 and t_2 we have

$$t_1 = 500 - (3382 \times .07473) = 247.30°C.$$

$$t_2 = 20 + (3382 \times .0672) = 247.27°C.$$

By using new adjusted values of $t_1 = 250°C.$ and $t_2 = 248°C.$ and computing a new value of β_2, new values of t_1 and t_2 are computed and are found to be $t_1 = 248.9°C.$ and $t_2 = 248.5°C.$ which are sufficiently close to the assumed (adjusted) values of t_1 and t_2 to be considered a solution.

The temperature indicated by a pyrometer placed in the duct is by the nature of the instrument, the temperature of its heat sensitive element, which temperature adjusts itself until the amount of heat supplied it by the sweeping of the gas is equal to that radiated from it to the relative cool wall of the duct, that is,

$$\beta_1 (t_0 - t_p) = R (t_p - t_1)$$

from which we get

$$t_p = t_1 + \frac{(t_0 - t_1)}{1 + \left(\frac{R}{\beta_1}\right)}$$

If we assume a mean temperature t_m between t_p and t_1 equal to 290°C., we have from Plate III, R = 26.0 and from previous computations, $\beta_1 = 14.16$. Therefore

$$t_p = 248.9 + \left[\frac{(500 - 248.9)}{1 + \left(\frac{26}{14.16}\right)}\right] = 337.4°C.$$

FIGURE 1—ROCKER ARM-FAILED IN SERVICE DUE TO STRESS CORROSION IN SEA WATER. CHEMICAL ANALYSIS— CU 56.61%, AL 1.91%, FE 1.16%, MN 1.70%, ZN 38.62%.

FIGURE 2—PHOTOMICROGRAPH X50 ILLUSTRATING AN INTERCRYSTALLINE CRACK IN THE BETA MICROSTRUCTURE OF ROCKER ARM.

FIGURE 3—LEVER ARM—FAILED IN SERVICE DUE TO STRESS CORROSION IN SEA WATER. CHEMICAL ANALYSIS—CU 54.68%, AL 0.78%, FE 1.15%, MN 1.60%, ZN 41.79%.

FIGURE 4—PHOTOMICROGRAPH X50 ILLUSTRATING AN INTERCRYSTALLINE CRACK IN THE BETA MICROSTRUCTURE OF LEVER ARM.

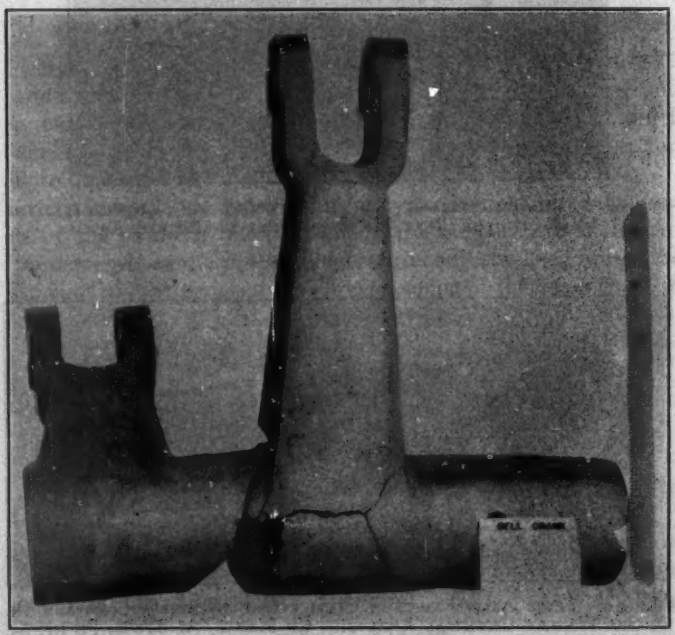


FIGURE 5—BELL CRANK—FAILED IN SERVICE DUE TO STRESS CORROSION IN SEA WATER. CHEMICAL ANALYSIS—CU 55.87%, AL 1.12%, FE 1.45%, MN 1.96%, ZN 39.30%.

FIGURE 6—PHOTOMICROGRAPH X50 ILLUSTRATING AN INTERCRYSTALLINE CRACK IN THE BETA MICROSTRUCTURE OF BELL CRANK.

FIGURE 7—PHOTOMICROGRAPH ILLUSTRATING A TYPICAL FRACTURED SURFACE PRODUCED IN BETA MANGANESE BRONZE BY STRESS CORROSION.

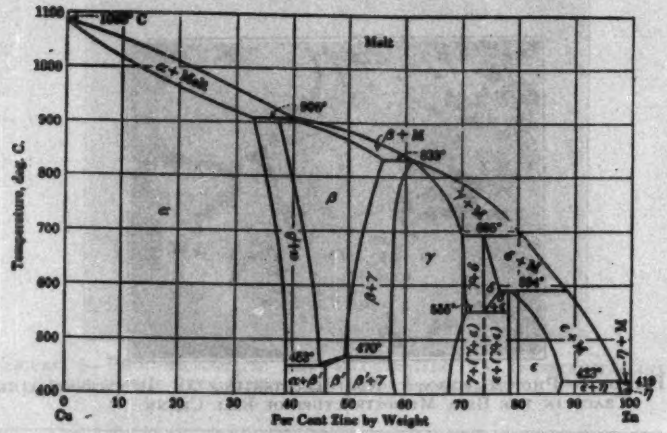


FIGURE 8—COPPER-ZINC EQUILIBRIUM DIAGRAM.

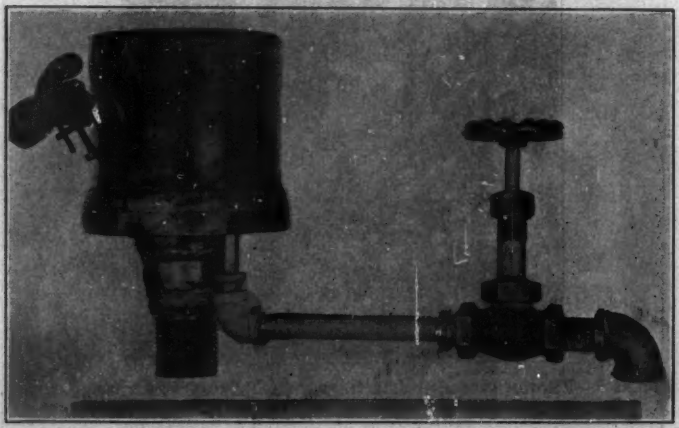


FIGURE 9—PHOTOGRAPH OF JIG USED WHEN SPECIMENS WERE TESTED UNDER CONTINUED LOAD IN TENSILE TESTING MACHINE.

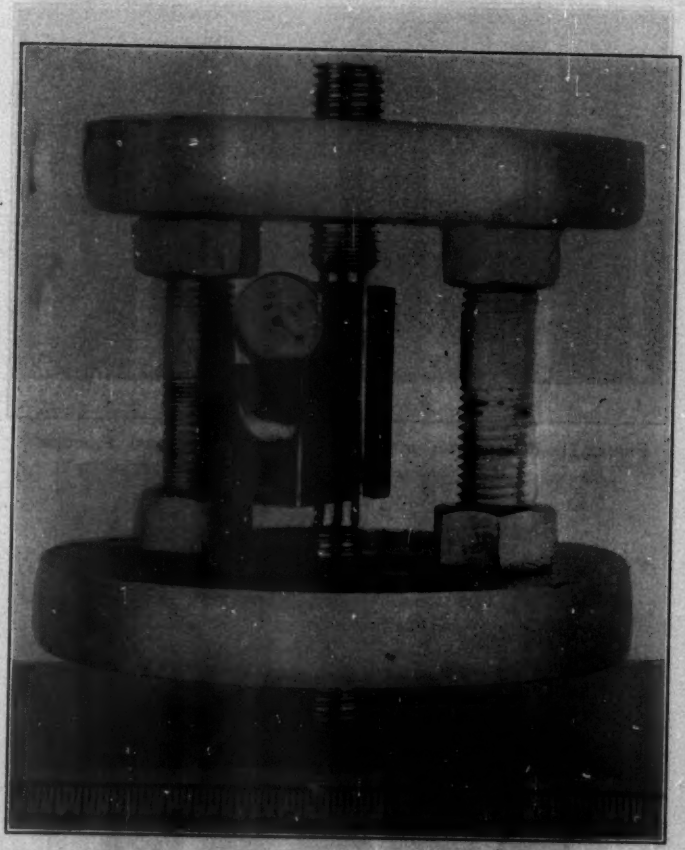


FIGURE 10—PHOTOGRAPH OF CHROME PLATED JIG USED INDEPENDENTLY OF TENSION MACHINE EXCEPT FOR ORIGINAL LOADING.

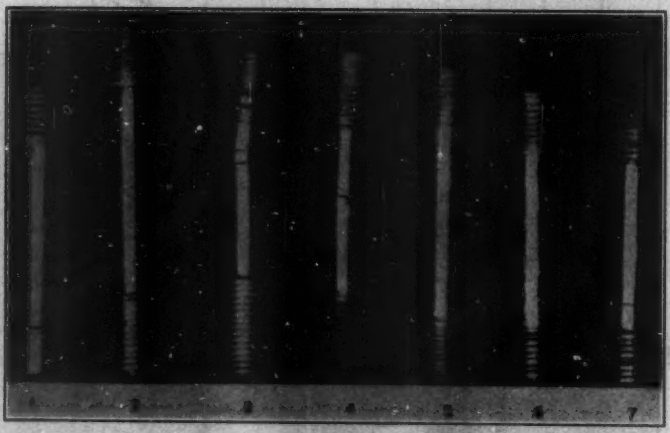


FIGURE 11—PHOTOGRAPH OF BETA SPECIMENS (1-7) AFTER FAILURE.

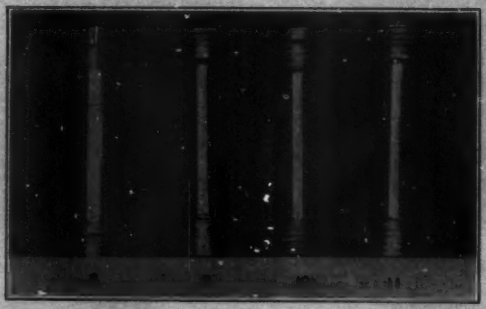


FIGURE 12—PHOTOGRAPH OF BETA SPECIMENS (8-11) AFTER FAILURE.

FIGURE 13—PHOTOGRAPH OF BETA SPECIMENS (12-19) AFTER FAILURE.

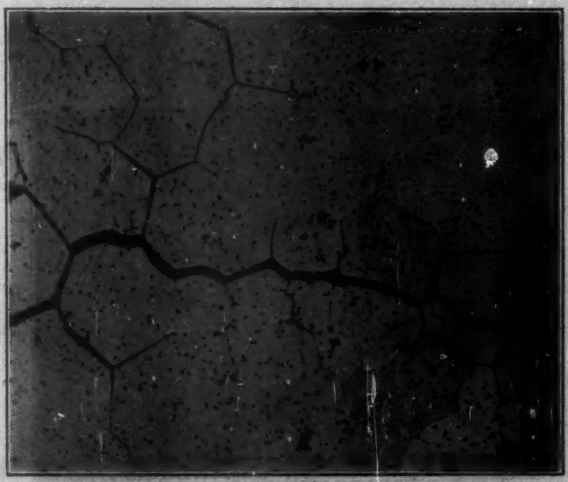


FIGURE 14—PHOTOMICROGRAPH X50 OF SPECIMEN 14 ILLUSTRATING AN INTERCRYSTALLINE CRACK IN A BETA MICROSTRUCTURE. TYPICAL OF STRESS CORROSION FAILURES IN SEA WATER FOR ALL BETA SPECIMENS.

FIGURE 15—PHOTOGRAPH OF ALPHA BETA SPECIMENS (20-24) AFTER FAILURE.

FIGURE 16—PHOTOMICROGRAPH X50 OF SPECIMEN 24 ILLUSTRATING A TRANSCRYSTALLINE CRACK IN AN ALPHA BETA MICROSTRUCTURE. TYPICAL OF STRESS CORROSION FAILURES IN SEA WATER FOR ALL ALPHA BETA SPECIMENS—ETCHED IN FERRIC CHLORIDE.

Assuming a second mean temperature, $t_m = 293°C.$, we find $R = 27.0$ and a second value of t_p is computed to be 335°C. This is sufficiently close (2°C.) to the assumed temperature (if $t_m = 293°C.$, then $t_p = 337°C.$) to warrant no further computation.

It is determined, therefore, that a pyrometer or thermometer placed in a duct passing hot air indicates a temperature only a few degrees above that of the wall of the duct, a fact which has long been recognized by engineers yet almost always neglected by personnel charged with the operation of industrial equipment. The above statement, while a rather important conclusion of the foregoing development, is of little more than academic interest to an engineer confronted with the task of determining the temperature of heated air passing through a duct. It becomes necessary, therefore, to work the solution in reverse and as fortune would have it, the reverse of the solution is the more simple.

Taking the same example duct as used previously, let us suppose three determinations are made by direct measurements.[8]

$$t_2 = 248.5°C.$$

$$t_p = 335°C.$$

$$V = 9.4 \text{ meters per second}$$

It has been shown that the temperature of the pyrometer will adjust itself until

$$\beta_1 (t_0 - t_p) = R (t_p - t_1)$$

or

$$\beta_0 (p) (t_0 - t_p) = R (t_p - t_1)$$

from which we get

$$t_0 = \frac{R (t_p - t_1)}{\beta_0 (p)} + t_p \qquad (J)$$

It is only necessary, therefore, to solve for values of R, t, β_0 and p to compute t_0.

If $t_2 = 248.5°C.$, then $s = 228.5°C.$ and from Plate IV $\alpha = 3500$. Thus

$$\beta_2 = \left(\frac{\alpha}{s}\right) = \left(\frac{3500}{228.5}\right) = 15.30$$

[8] It is admitted that the measurement of values of t_2 and V require no small degree of technique.

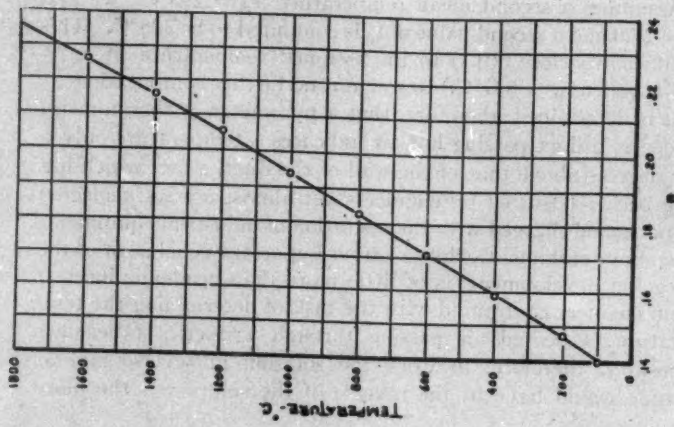


PLATE II.

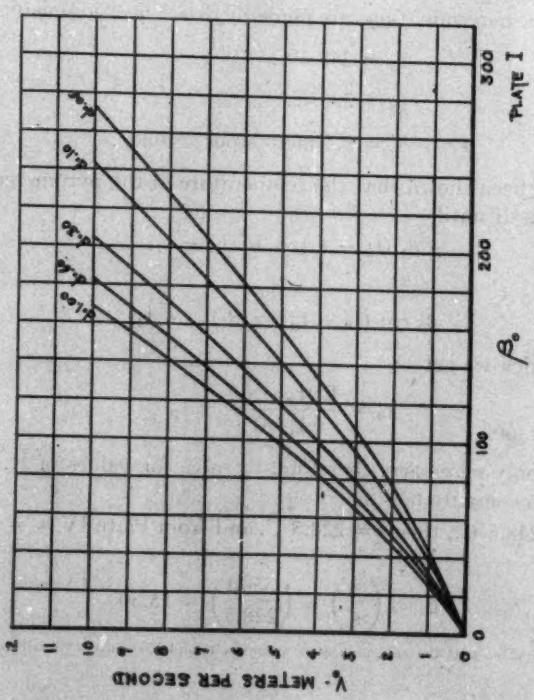


PLATE I

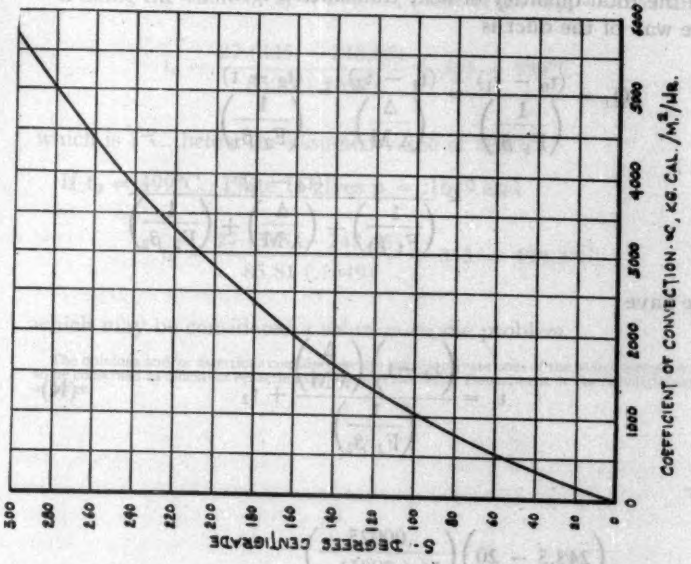


PLATE IV.

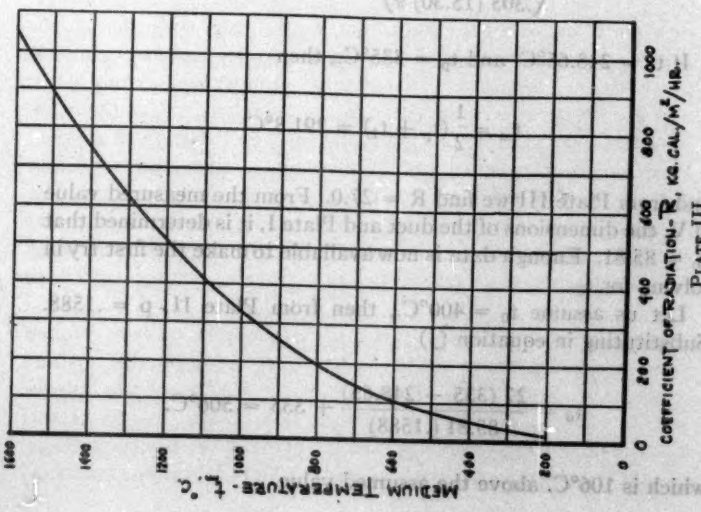


PLATE III.

As the total quantity of heat transmitted from the gas through the wall of the duct is

$$Q_T = \frac{(t_0 - t_1)}{\left(\frac{1}{F_1\ \beta_1}\right)} = \frac{(t_1 - t_2)}{\left(\frac{\Delta}{\lambda\ M}\right)} = \frac{(t_2 - t)}{\left(\frac{1}{F_2\ \beta_2}\right)}$$

$$= \frac{(t_0 - t)}{\left(\frac{1}{F_1\ \beta_1}\right) + \left(\frac{\Delta}{\lambda\ M}\right) + \left(\frac{1}{F_2\ \beta_2}\right)}$$

we have

$$t_1 = \frac{\left(t_2 - t\right)\left(\frac{\Delta}{\lambda\ M}\right)}{\left(\frac{1}{F_2\ \beta_2}\right)} + t_2 \qquad (K)$$

or

$$t_1 = \frac{\left(248.5 - 20\right)\left(\frac{.00025}{36\ (.3025)\ \pi}\right)}{\left(\frac{1}{.305\ (15.30)\ \pi}\right)} + 248.5 = 248.65°C.$$

If $t_1 = 248.65°C.$ and $t_p = 335°C.$, then

$$t_m = \frac{1}{2}(t_p + t_1) = 291.8°C.$$

and from Plate III we find R = 27.0. From the measured value of V, the dimensions of the duct and Plate I, it is determined that $\beta_0 = 85.81$. Enough data is now available to make the first try in solving for t_0.

Let us assume $t_0 = 400°C.$, then from Plate II, p = .1588. Substituting in equation (J)

$$t_0 = \frac{27\ (335 - 248.65)}{85.81\ (.1588)} + 335 = 506°C.$$

which is 106°C. above the assumed value.

Taking the value of $t_0 = 506°C.$, Plate II gives $p = .1652$ and

$$t_0 = \frac{27\,(335 - 248.65)}{85.81\,(.1652)} + 335 = 499°C.$$

which is 7°C. below the assumed value of 506°C.

If $t_0 = 499°C.$, Plate II gives $p = .1649$ and

$$t_0 = \frac{27\,(335 - 248.65)}{85.81\,(.1649)} + 335 = 499.3°C.$$

which may be considered a solution to the problem.

The opinions and/or assertions contained herein are the private ones of the writer and are not to be construed as official or reflecting the views of the Navy Department or the Naval Service at large.

STRESS CORROSION OF MANGANESE BRONZE CASTINGS IN SUBMARINE SERVICE.

By Thomas L. Sheehan and Howard E. Dickerman.

Manganese bronze castings, if stressed above the yield strength while immersed in sea water, are subject to stress corrosion. The percentage composition of the alloying elements or, specifically, the microstructure of the bronze, plays an important part in determining its susceptibility to stress corrosion. Beta bronze is far more sensitive to stress corrosion in sea water than are the bronzes of alpha beta microstructure.

Manganese bronze made in accordance with Navy Department Specification 49B3e of 1 Nov. 1939 has been used extensively for castings requiring high strength and corrosion resistance to sea water. Its use was further extended to replace alloys made from nickel and copper during the early part of World War II when conservation of these critical materials was imperative. Manganese bronze, because of its excellent strength properties and high corrosion resistance to sea water, was employed for such parts as bell cranks, rocker arms, lever arms, linkage castings, propellers, torpedo tube operating mechanisms and other applications where high strength and corrosion resistance are desirable properties. These types of castings are operated in sea water and are designed with a factor of safety calculated to maintain the stress well below the yield strength of the part in service. However, it is believed that due to some unforeseen condition such as a defective casting or misalignment produced by a blow or shock, stresses well below the tensile strength but in excess of the yield strength of certain castings of this type were developed while the parts were submerged in sea water, causing ultimate failure.

During the past three years approximately twenty broken castings of the types noted above have come to the authors attention. It appeared highly significant that all of the failures had occurred in castings which were operated in sea water and not one failure had been reported for manganese bronze castings, of similar design, operated inboard. Metallographic examina-

tion and chemical analysis, in each case, disclosed that the castings had been alloyed with zinc and aluminum in sufficient quantities to produce complete beta microstructures. It was further revealed that all castings failed in a brittle manner without any indication of bending or stretching and that the path of the cracks, in each case, followed grain boundaries.

The results of these early investigations led us to believe that this type of failure was due to the simultaneous action of stress and sea water on beta bronzes only, and that manganese bronze of alpha beta microstructure was not affected by these conditions. Guided by this opinion, control methods were devised in the melting room of the foundry to limit the composition of the alloy to a desired chemical analysis of approximately 58 per cent copper, 39 per cent zinc, 0.80 per cent aluminum, 1 per cent manganese and 1.2 per cent iron. This analysis conforms to the Navy Department Specification 49B3e which gives the following limits: copper—55-60 per cent, lead—0.40 per cent (max.), aluminum—1.50 per cent (max.), manganese—3.50 per cent (max.), iron—0.40-2.00 per cent, tin—1.00 per cent (max.), other elements—0.20 (max. of each), zinc—remainder.

Many of our manganese bronze castings were supplied by commercial foundries and one supplier was using ingot metal containing aluminum on the high side of the specification limit for that element. Some heats were just within the 1.50 per cent maximum allowed, others contained up to 2.00 per cent, and with a zinc content ranging from 37 to 39 per cent, the microstructures were completely beta. A typical analysis of one of these foundries' castings was: copper—58.40 per cent, aluminum—1.54 per cent, iron—1.29 per cent, manganese—0.36 per cent, zinc—38.41 per cent, and tin—trace. This analysis, although within limits of Navy Department Specification 49B3e except for an excess of .04 per cent aluminum, produces a beta microstructure.

Before taking up the test work conducted in the laboratory to reproduce similar types of failures and to investigate stress corrosion in relation to lower strength alpha beta bronzes, it is considered timely to present a few illustrations of these failures, the microstructures involved and an explanation of the composition diagram related to the copper-zinc system.

Figures 1 to 6 inclusive present photographs in which the broken castings, their microstructures and chemical analyses are

shown. Figure 7 illustrates a typical stress corrosion facture of beta bronze in which the geometric outline of the grain structure can be seen.

Figure 8 is an equilibrium diagram of copper and zinc and indicates the combinations of these elements necessary to form the various microstructures. The diagram shows that the alpha beta range, under equilibrium conditions, extends from 39 per cent to 46 per cent zinc, and the beta range extends from 46 per cent to 50 per cent zinc. A fairly rapid rate of cooling of the molten metal in the mold has a tendency to shift the diagram to the left. This condition reduces the zinc content necessary to produce similar microstructures as those under equilibrium conditions by approximately 1 per cent. Aluminum added to copper-zinc alloy is approximately six times as effective as zinc also in advancing the microstructure to the right. To illustrate the latter, a 41 per cent zinc alloy is normally alpha beta but with the addition of 1 per cent aluminum a zinc equivalent of 47 per cent zinc will result and a beta microstructure will be formed. The iron and manganese in the usual percentages found in manganese bronze have little or no effect on the microstructure in respect to the percentages of alpha or beta present.

Selection of Material for Test.

The sources of the specimens used in the test conducted in the laboratory are given in the following paragraphs and chemical analyses of these heats are included in Table No. 2.

Specimens numbered 1 to 7 inclusive (beta bronze) were obtained from a rocker arm casting which was sent to the laboratory for examination after it had failed in service. This casting, illustrated in Figure 1, is used to support the muzzle door on a submarine torpedo tube. In service, it is totally submerged and under constant stress while maintaining the door in a closed position.

Specimens 8 to 11 inclusive were obtained from a special heat of manganese bronze cast in the Portsmouth Naval Shipyard foundry. This heat was prepared from a mixture calculated to produce a beta microstructure.

Specimens 20 to 24 inclusive were obtained from a special heat of manganese bronze cast in the Portsmouth Naval Shipyard foundry and were produced from a mixture which was calculated to give an alpha beta microstructure.

Preparation of Specimens and Construction of Jigs.

One specimen obtained from each casting or heat was examined for microstructure and tested for physical properties. The remaining specimens were tested for stress corrosion data.

A jig was constructed as shown in Figure 9 to be used in connection with test specimens held under continuous load in a tension machine. Any desired load could be applied to the specimen and the level of the sea water could be maintained at any position. The sea water was changed twice weekly and the level regulated by a drain valve located in the bottom of the jig.

In order to expedite the test several jigs similar to that shown in Figure 10 were designed which allowed the specimens to be maintained under load independent of the testing machine. In this setup the jig assembly was fixed to the top and bottom platens of the testing machine and, with an extensometer fastened to the specimen, a predetermined tension load, below the yield strength, was applied. The spacer bolts were then tightened permitting the load indicator of the machine to fall off to zero, thereby shifting the load to the spacer bolts and the specimen under test. There was no movement of the extensometer dial indicator fastened to the specimen which was evidence that the specimen was being maintained under the original load as applied by the tension machine. The jig assembly was then unscrewed from the tension machine and, after removing the extensometer, the assembly was submerged in a hard rubber tank containing sea water.

It was not possible to ascertain any relaxation of the load after the extensometer was removed from the specimens tested in the jigs, Figure 10. However, in the case of specimens tested in jig, Figure 9, relaxation of the load, as indicated by the dropping of the beam, was overcome by reloading until the beam again came into balance. It appeared that very little creep was encountered in either method and the results of test indicated that both methods were satisfactory.

The loading procedure was varied from heat to heat and in instances where several duplicate specimens were available, the procedure was changed, for certain of these specimens, to furnish as much information as possible. However, the procedure generally consisted of loading to a value below the yield strength of the particular specimen which was then immersed in sea water

for a certain period of time and if no cracks were observed at the end of that period the load was increased to a higher value and immersion continued, etc. until failure occurred. The yield strength of these specimens was determined from the duplicate specimens tested in air and is taken as that load which produces an elongation of .01 inch in a two inch gage length while the specimen is under a tension load.

The data compiled from physical tests conducted in the laboratory for specimens tested under varying conditions are given in Table No. 1.

Photographs illustrating the condition of the specimens and typical microstructures after test are shown in Figures 11 to 16 inclusive. Specimens 1 and 2 of Figure 11 were tested in laboratory atmosphere. Specimens 3, 4, 6 and 7 were tested in sea water. Specimen 5 was maintained under load in sea water for a period of eight days (its yield strength was exceeded during the last two days of this period) and when no visible cracks were noted at the end of this time the specimen was removed from the sea water and broken in atmosphere. Specimens 8 to 19 inclusive shown in Figures 12 and 13 were tested in sea water. Photomicrograph Figure 14 illustrates an intergranular crack contained in specimen No. 14. Specimen 20 of Figure 15 was tested in laboratory atmosphere while specimens 21 to 24 were tested in sea water. The photomicrograph, Figure 16, shows the nature of the crack which was examined on specimen 24 and indicates that the path of the crack lies in a plane through the grains. In this respect, it appears that the weakness of the alpha beta bronzes to stress corrosion is along crystallographic planes whereas grain boundaries are the source of weakness in the beta specimens.

The results of this test indicate that, irrespective of microstructure, manganese bronze is sensitive to stress corrosion in sea water, the failures occurring at loads somewhat in excess of the yield strength of the metal. It will be observed, however, that the alpha beta bronzes are less sensitive to these conditions than bronzes of the complete beta microstructure. A study of Table No. 1 discloses that an average maximum load of 1594 pounds per square inch in excess of the yield strength was applied to the beta specimens, whereas the average maximum load in excess of the yield applied to the alpha beta specimens was 8625 pounds per square inch.

TABLE No. 1

PHYSICAL POPERTIES OF MANGANESE BRONZE TESTED UNDER VARYING CONDITIONS OF LOADING IN ATMOSPHERE AND SEA WATER

Specimen Number	Medium	Loading Method (Time)	Sea Water Immersion Days	Sea Water Immersion Load, psi	Tensile Strength psi	Yield Strength psi	% Elongation in 2"
			BETA SPECIMENS				
1	Atmosphere	At once	..	.....	85,750	39,750	16.5
2	Atmosphere	Prolonged	21	37,500	.....	.....	....
	Atmosphere	Prolonged	14	40,000	.....	.....	....
	Atmosphere	Prolonged	4	42,500	87,000	.....	25.0
3	Sea water	Prolonged	11	25,000	.....	.....	....
	Sea water	Prolonged	7	32,500	.....	.....	....
	Sea water	Prolonged	7	37,500	.....	.....	....
	Sea water	Prolonged	4	45,000	(crack in fillet at water level)		
4	Sea water	Prolonged	12	37,500	(crack in gage length at water level)		
5	Atmosphere	Prolonged	6*	37,500	.....	.....	....
	Sea water	Prolonged	6	37,500	.....	.....	....
	Sea water	Prolonged	2	40,000	.....	.....	....
	Atmosphere	At once	..	.....	85,000	.....	18.0

*Under load in atmosphere

TABLE No. 1 (continued)

Specimen Number	Medium	Loading Method (Time)	Sea Water Immersion Days	Sea Water Immersion Load, psi	Tensile Strength psi	Yield Strength psi	% Elongation in 2″
6	Sea water	Prolonged	7	25,000	.....	.....	....
	Sea water	Prolonged	7	27,500	.....	.....	....
	Sea water	Prolonged	7	30,000	.....	.....	....
	Sea water	Prolonged	5	32,500	.....	.....	....
	Sea water	Prolonged	5	35,000	.....	.....	....
	Sea water	Prolonged	7	37,500	.....	.....	....
	Sea water	Prolonged	2	40,000	(severely cracked)		2.0
7	Sea water	Prolonged	7	25,000	.....	.....	....
	Sea water	Prolonged	7	27,500	.....	.....	....
	Sea water	Prolonged	7	30,000	.....	.....	....
	Sea water	Prolonged	7	32,000	.....	.....	....
	Sea water	Prolonged	7	35,000	.....	.....	....
	Sea water	Prolonged	10	37,500	.....	.....	....
	Sea water	Prolonged	3	40,000	(small cracks)		1.0
8A	Atmosphere	At once	..	.....	85,750	38,000	18.5
8	Sea water	Prolonged	3	39,000	(cracked)		0
9	Sea water	Prolonged	6	39,000	(cracked)		2.0
10	Sea water	Prolonged	4	40,000	(fractured)		1.0

TABLE No. 1 (continued)

TABLE No. 1 (continued)

Specimen Number	Medium	Loading Method (Time)	Sea Water Immersion Days	Sea Water Immersion Load, psi*	Tensile Strength psi	Yield Strength psi	% Elongation in 2"
11	Sea water	Prolonged	12	40,000	(fractured)		4.0
12A	Atmosphere	At once	..	.....	87,500	32,250	25.0
12	Sea water	Prolonged	7	32,500	.....	.....	....
	Sea water	Prolonged	7	35,000	.....	.....	....
	Sea water	Prolonged	1	37,500	(cracked)		3.5
13A	Atmosphere	At once	..	.....	87,100	38,000	22.0
13	Atmosphere	Prolonged	2*	35,000	.....	.....	....
	Sea water	Prolonged	7	35,000	.....	.....	....
	Sea water	Prolonged	7	37,500	.....	.....	....
	Sea water	Prolonged	..	40,000	(fractured in 2 hrs.)		2.0
14A	Atmosphere	At once	..	.....	85,000	36,250	21.0
14	Atmosphere	Prolonged	7*	36,000	.....	.....	....
	Sea water	Prolonged	..	36,000	(fractured overnight)		0
15A	Atmosphere	At once	..	.....	88,000	28,250	27.5
15	Atmosphere	Prolonged	3*	27,500	.....	.....	....
	Atmosphere	Prolonged	1*	30,000	.....	.....	....
	Sea water	Prolonged	..	30,000	(fractured overnight)		0

*Under load in atmosphere

TABLE No. 1 (continued)

Specimen Number	Medium	Loading Method (Time)	Sea Water Immersion Days	Sea Water Immersion Load, psi	Tensile Strength psi	Yield Strength psi	% Elongation in 2"
16A	Atmosphere	At once	..	.....	85,500	35,750	21.0
16	Sea water	Prolonged	10	35,000	.....	.....	....
	Sea water	Prolonged	7	37,500	(small crack)		5.5
17A	Atmosphere	At once	..	.....	85,500	35,750	20.0
17	Atmosphere	Prolonged	5*	35,000	.....	.....	...
	Sea water	Prolonged	7	35,000	.....	.....	....
	Sea water	Prolonged	1	37,500	(fractured at water level)		1.5
18A	Atmosphere	At once	..	.....	85,000	37,000	20.5
18	Atmosphere	Prolonged	6*	32,500	.....	.....	....
	Atmosphere	Prolonged	7*	35,000	.....	.....	....
	Sea water	Prolonged	5	35,500	.....	.....	....
	Sea water	Prolonged	8	37,500	(severely cracked)		1.5
19A	Atmosphere	At once	..	.....	88,500	28,750	29.0
19	Sea water	Prolonged	14	27,500	.....	.....	....
	Sea water	Prolonged	14	28,000	.....	.....	....
	Sea water	Prolonged	2	30,000	(fractured)		3.0

*Under load in atmosphere

TABLE No. 1 (continued)

		Loading	Sea Water		Tensile	Yield	%

TABLE No. 1 (continued)

Specimen Number	Medium	Loading Method (Time)	Sea Water Immersion Days	Sea Water Immersion Load, psi	Tensile Strength psi	Yield Strength psi	% Elongation in 2″
		ALPHA BETA SPECIMENS					
20A	Atmosphere	At once	..	.....	68,750	28,000	28.0
21	Sea water	Prolonged	20	28,000	.....	.....	....
	Sea water	Prolonged	20	29,000	.....	.....	....
	Sea water	Prolonged	20	30,000	.....	.....	....
	Sea water	Prolonged	20	32,500	.....	.....	....
	Sea water	Prolonged	16	35,000	(slight cracks)		11.0
22	Sea water	Prolonged	20	28,000	.....	.....	....
	Sea water	Prolonged	20	29,000	.....	.....	....
	Sea water	Prolonged	20	30,000	.....	.....	....
	Sea water	Prolonged	20	32,500	.....	.....	....
	Sea water	Prolonged	16	35,000	(slight cracks)		8.0
23	Atmosphere	Prolonged	7	30,000	.....	.....	....
	Sea water	Prolonged	10	32,500	.....	.....	....
	Sea water	Prolonged	21	35,000	.....	.....	....
	Sea water	Prolonged	28	37,500	(fractured)		6.5
24	Atmosphere	Prolonged	2	30,000	.....	.....	....
	Sea water	Prolonged	4	30,000	.....	.....	....
	Sea water	Prolonged	10	32,500	.....	.....	....
	Sea water	Prolonged	12	35,000	.....	.....	....
	Sea water	Prolonged	8	37,500	.....	.....	....
	Sea water	Prolonged	8	39,000	(fractured)		8.0

TABLE NO. 2.

CHEMICAL ANALYSES OF DUPLICATE SPECIMENS TAKEN FROM SAME HEAT AS THOSE USED FOR STRESS CORROSION TEST.

	Chemical Analyses					
Specimen No.	Copper	Alumi-num	Iron	Man-ganese	Zinc	Tin
1-7 (incl.)	56.61	1.91	1.16	1.70	38.62	....
8	56.54	1.75	0.78	0.36	40.57	....
9	56.54	1.75	0.78	0.36	40.57	....
10	56.54	1.75	0.78	0.36	40.57	....
11	56.54	1.75	0.78	0.36	40.57	....
12	56.12	0.90	1.07	0.48	41.43	....
13	58.60	1.64	1.20	0.40	38.16	....
14	56.14	1.54	1.20	0.68	40.44	....
15	54.37	1.50	1.29	0.67	42.17	....
16	57.31	1.16	1.00	0.44	40.09	....
17	53.73	1.31	1.35	0.48	43.13	....
18	57.80	1.66	1.24	0.39	38.91	....
19	55.34	1.45	1.10	0.52	41.59	....
20-24 (incl.)	58.53	0.79	0.73	0.09	39.86	trace
Required	55-60	0.50-1.50	0.40-2.00	1.50 max.	Rem.	1.00 max.

In respect to the ductility of the two types of bronzes, it was calculated from Table No. 1 that the average elongation of the beta specimens was 1.9 per cent while the average for the alpha beta specimens was 8.4 per cent. The superior ductility of the alpha beta bronze as determined by this test may account for its satisfactory use in outboard castings. It will be noted that specimen No. 5 was removed from the sea water after an immersion period of 8 days. During the total immersion period it had been stressed to 37,500 PSI for 6 days (2000 PSI below its yield) and 2 days at 40,000 PSI. Apparently the specimen had not been attacked as evidenced by the tensile and elongation values of 85,000 pounds per square inch and 18 per cent respectively which were obtained on testing the specimen to destruction in laboratory atmosphere. This test indicates that slight overloading in sea water will not produce a stress corrosion failure unless sufficient time is allowed for corrosion to take place. A comparison of the immersion periods of alpha beta bronze with the

immersion periods of complete beta bronze further indicates the superiority of alpha beta bronze under stress in sea water. A study of Table No. 1 shows that the average immersion period for the beta bronze specimens maintained at loads in excess of their yield strength was 4.31 days while the same for the alpha beta bronzes was 83.25 days.

Although this test reveals that manganese bronze of the alpha beta type and the beta type are both susceptible to stress corrosion in sea water, it is considered that emphasis should be placed on the results of examination of the many castings that failed in service. The significance of these repeated failures in this type of bronze would seem to be that beta bronze is extremely sensitive to stress corrosion in sea water whereas the lower strength alpha beta bronze does not fail under actual service conditions.

It is considered that the reasons for the superior resistance of the alpha beta bronzes to stress corrosion in sea water may be related to one or more facts brought out by this test. First, let us compare the failure of the alpha beta bronze and the complete beta bronze with respect to the location of the cracks. It was shown in the alpha beta specimens, Figure 16, that the cracks penetrated the grains along crystallographic planes while the cracks as shown in the beta specimen, Figure 14, were intercrystalline. It appears probable that there is less anodic material along these crystallographic planes and that they are less favorably oriented to permit the penetration of the sea water. In the relationship of cracking to selective corrosion, it is possible that the cracks follow that part of the structure which is the weakest physically, and is the first to yield. If this is true, yielding occurs first along the slippage planes in the alpha beta bronze whereas in the beta bronze the yielding is confined to the grain boundaries and since the corrosion is selective of those areas wherein plastic deformation is continually occurring, the cracks follow these highly stressed areas. The second consideration is concerned with the ductility of the two types of bronze. Stress-strain curves which were plotted from the test of duplicate specimens indicated that the alpha beta bronzes commenced to yield at very low loads showing practically no elastic range whereas all beta bronze specimens showed an elastic limit of values between 17,500 and 27,500 PSI. The plastic deformation occurring at

low loadings in the alpha beta specimens may have accounted for a relaxation of the stress thereby reducing it to some value below the critical "stress corrosion" load. Although this consideration could not apply for specimens No. 23 and No. 24 tested in the laboratory where any relaxation was compensated by the balancing of the beam, still it may have accounted for satisfactory use of the alpha beta bronze in service.

Conclusions.

Manganese bronze castings conforming to Navy Department Specification 49B3e (or to the latest Navy Department Specification 49B3f) may be alloyed with a combination of elements to produce either an alpha beta or complete beta microstructure. Both types of bronze will fail by stress corrosion in sea water but the alpha beta type is less sensitive to these conditions than the complete beta bronze.

The maximum average loads in excess of their yield strengths withstood by these types of bronzes were 1594 PSI for beta bronze and 8625 PSI for alpha beta bronze.

The maximum average elongations obtained for alpha beta bronze and beta bronze tested under stress corrosion conditions were 1.9 per cent and 8.4 per cent respectively.

The average immersion periods under stress corrosion conditions for these bronzes were 4.31 days for beta bronzes and 83.25 days for alpha beta bronzes.

The failures of the beta bronze occur around grain boundaries while the failures in the alpha beta bronzes are transcrystalline.

MECHANICAL SHOCK ON NAVAL VESSELS AS RELATED TO EQUIPMENT DESIGN.

By W. P. Welch.*

I. Introduction.

Reliable operation of the machinery and equipment in a naval vessel under severe conditions of mechanical shock is one of the several unusual design requirements that must be satisfied by naval apparatus. This shock requirement has long been recognized, at least in a qualitative manner. However, during World War II combatant ships encountered shock conditions of intensities heretofore not expected, as the result of the non-contact underwater explosion of large charges employed in influence mines and in aerial bombs. As a consequence of these experiences, shockproof designs for important components of shipboard machinery and equipment have been investigated and developed. This article will present the basic physical factors relating to shock and will briefly describe some of the engineering achievements during the period 1941 through 1945.

The elemental source of shock is the sudden application of external forces to a portion of the ship's structure. The term "shock" is herein applied to the sudden, transient motion of an item of machinery or equipment as transmitted by the foundation or the mounting from the ship's structure. Thus the term "shock" will be employed in a relatively restricted sense, and in this manner does not include the destruction of a ship's structure by means of direct exposure to an explosion, or the damage to equipment as the result of collision of a projectile or other object, or damage due to extreme distortion of the foundation.

It is self-evident that severe shock damage to the ship's machinery and equipment may have fatal consequences. Therefore in establishing the criterion for shock resistance, the following principle has been adopted as fundamental: the machinery and equipment should be capable of continued, uninterrupted operation under conditions of shock up to that intensity which would cause uncontrollable flooding of the ship's hull.

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II. War Experience.

Shock effect investigations prior to the recent war were related primarily to two causes, namely: (a) the firing of the ship's own guns, and (b) the impact of projectiles upon armored spaces such as turrets and the ship's armored box. Appreciable progress had been made in mitigating damage due to these causes, usually by means such as mounting the equipment clear of armor, and clear of bulkheads and decks directly exposed to gun blast shock. Even so, the effect of gun blast shock still remains a serious problem, and considerable damage due to this cause was experienced in World War II.

However, the source of extensive and crippling shock damage is now considered to be the non-contact underwater explosion, especially inasmuch as shock from this cause is most severe on equipment located in the spaces near or below the water-line of the ship. Several of the most severe cases of shock damage to U. S. naval vessels will now be reviewed, for the purpose of illustration.

The first case for consideration is a destroyer of the Somers Class. The ship was operating off of the Normandy beachhead when an acoustic mine exploded abreast the No. 4 gun mount about 50 to 100 feet to port. The depth of water was 65 feet, the mine probably having exploded at that depth. As a result of the explosion the entire after portion of the ship was subjected to severe shock, the after port area of the underwater hull plating being dished inward from frames 83 to 136. There were no ruptures in the hull caused by the explosion, although in the vicinity of the deflected plating, shell frames were twisted and numerous bulkheads were distorted. Both main engines developed loud grinding noises due to misalignment of the reduction gears. However, despite the noises, the engines were capable of being operated immediately after the event.

The shock effects were of serious consequence, as will be seen from the following listing:

(a) All vacuum was lost on both main condensers due to numerous leaks in piping resulting from shock. Twelve hours were required to repair this damage.

(b) The main generators stopped, due probably to shock effect on the turbine throttle valve latching and tripping mechanisms.

(c) All circuit breakers on the main switchboard tripped.

They were immediately reset but would not stay in. Upon investigation, it was found that a short length of bare wire had fallen into the buswork, subsequently causing a serious fault that burned up three smaller circuit breakers.

(d) During loss of power due to (c), power was supplied by the emergency generators, which, however, did not start and run automatically as designed, due to shock damage to the controls of both machines.

(e) Several motor controllers for electric pumps were put out of commission by dislodgement of the arc chutes and consequent jamming of the contacts.

(f) Numerous supports and braces to steam lines and machinery failed. Several pipes and ventilation ducts were bent and ruptured.

(g) The port steering motor pump set was misaligned due to distortion of the foundation.

(h) The 36 inch searchlight was knocked off its base: the pintle bearing failed.

(i) Two radio receivers were severely damaged by extreme distortion of panels and framework, even though there was no structural damage in the compartment in which they were located.

(j) One radar put out of action due to fracture of insulating pieces.

(k) Master gyro compass developed a severe noise.

As a matter of further interest, there were no personnel casualties caused by the mine explosion. It therefore follows that practically all of the damage of immediate consequence was due to shock effects on machinery, the watertight integrity of the ship having not been impaired.

The second example is that of a submarine which was caught on the surface at night and forced down and subjected to a very severe depth charge attack. Over 40 depth charges were dropped in her vicinity, of which the last 12 were extremely close. The boat suffered not only much interior damage but sufficient hull damage to require major repairs by a yard.

The medium close depth charges broke lights, knocked cork off of the hull, broke fans from their bases, caused clocks to stop, and jarred light hull fittings loose. The last six charges were the closest and did most of the damage. Two of the charges

exploded directly over the engine rooms. The hull in the vicinity sprung in about 6 inches and the flapper valves of the engine induction system began to leak badly. The boat vibrated most severely and then settled to the bottom where she was silenced completely and the repair of damage begun.

Of the equipment damaged by shock, the following is a partial list:

(a) The hull induction system was flooded and the induction valves jammed closed.

(b) About 75 per cent of small items bolted directly to the hull were jarred loose.

(c) About 60 per cent of all gages and meters were made inoperative.

(d) Numerous lamps and several lighting fixtures failed.

(e) Both periscopes had cracked prisms.

(f) Rudder angle indicator, pitometer log, sound heads, fathometer, shaft revolution counters were made inoperative.

(g) One lube oil purifier and one pump motor failed.

An item not specifically detailed in this case, but reported by other submarines, is the backing off (or opening) of valves while the boat is under depth charge attack. In many cases, valves have been forced open under shock, causing relatively serious fluid transfer at a critical time.

Despite the apparent extent of the above shock damage, the performance of submarine equipment under most severe depth charge attacks has been excellent. Several boats have returned with their hulls distorted to the point of incipient failure, and yet the shock damage reported has been almost negligible.

As a third and final example, a large aircraft carrier operating in the Pacific was attacked by four suicide planes, two of which fell in the water alongside the ship. While the planes were sinking, their bombs exploded, subjecting the ship to severe shock from the non-contact underwater explosions. Although the hull damage was slight, the machinery damage was considerable. The No. 3 main engine was disabled due to fractured castings, and two of the turbo-generators were made inoperative, due also to fractured castings. The No. 1 diesel fire pump was torn free from all piping connections. A radar antenna collapsed. Considerable minor damage was reported.

The most serious of the above failures may be attributed to the use of cast iron or a low grade of cast steel for the affected castings, this ship having been constructed in the middle 30's, this being prior to the general elimination of cast iron for new construction vessels.

Although ships built to Navy standards did not suffer very seriously from shock damage during the war, such was not the case for several non-Navy design ships that were subjected to heavy non-contact mine explosions. Included in this category was a CVE which ran over a ground mine in European waters. The machinery and equipment of this ship were so badly disabled by shock that a major overhaul was required, despite the fact that the hull was not ruptured even slightly.

Furthermore, the British naval vessels experienced shock damage of alarming proportion and extent prior to our entry into the war. The determining causes were two-fold. First, the ships were operating in waters highly infested with influence mines, for which no effective counter-measures were then available. And second, cast iron was used extensively in the construction of both main and auxiliary machinery. In fact, the British estimated that 80 per cent of the shock failures consisted of the fracture of cast iron parts of machinery.

It might be generally stated that most of the cases of damage to U. S. ships during the war were the result of contact explosions, as caused by torpedoes, bombs and projectiles. For reasons that are still obscure, contact explosions produced little or no shock damage, although the structural damage and direct explosion damage is usually extensive. This fact is supported by both American and British war experience. In several cases, almost identical ships have been subjected one to a torpedo hit and the other to an influence mine explosion, the shock damage being negligible in the first case and yet severe in the second.

III. Generation of Shock.

In this section the more common circumstances under which severe shock is generated are discussed. The factors affecting the intensity and the character of the shock to which a particular item of equipment aboard a naval vessel will be subjected in a given action are many, these factors including the construction of the hull, the location of the equipment, its foundation and its weight. However, by far and wide the major factors involved

TABLE I—SOURCES OF SHOCK.

A.	Underwater Explosions		Direct Projectile or Bomb Hits		Firing of Ship's Guns	
B.	Contact	Non-contact	Full Penetration	Partial Penetration	Air Blast	Recoil Shock
C.	Torpedoes	Influence mines	.. Projectiles ..		.. Main battery ..	
	Contact mines	Aerial bombs (near-misses)	.. Aerial bombs ..		.. Secondary batteries ..	
		Depth charges				

are the proximity of the explosion, the weight of the charge, and the medium in which the explosion occurs, for these are the factors that, for a given ship, determine whether (1) no damage at all will be sustained, (2) shock damage to equipment will occur, or (3) whether there will be major hull damage.

The problem of developing by analysis or experiment a theory that describes the method of transmission of a shock wave through the complex structure of a ship's hull to a selected item of machinery within the ship is a most complex assignment. Little has been done on this problem in this country. In Great Britain, some work has been done but the results have not yet been published. Consequently, the phenomena associated with the transmission of the shock through the ship's structure will not be discussed herein. Suffice it to say that the actual shock motion as experienced by a given item of equipment is greatly influenced by the foundation or the mounting of the equipment (as well as by the other structure between the foundation and the hull). When a shock motion is imparted to the base of the foundation, the motion of the equipment will then consist of the shock motion of the foundation plus vibratory components determined by the stiffness and the shape of the foundation, these latter components in certain cases being the most damaging part of the shock.

The sources of shock may be classified in accordance with the conditions surrounding the explosion in the manner shown in Table I. Classification in this manner is indicated due to the considerable difference in shock to be expected from the six sources as listed in row "B" of the table.

Contact underwater explosions.—When an explosive charge is placed adjacent to the underwater exterior of a ship's hull and then is detonated, very favorable conditions exist to obtain severe local damage to the hull. In virtually all actual cases the charge weight is sufficiently great to rupture the outer shell in the region of the explosion. Except on those vessels having an elaborate torpedo protection system, the explosion of a torpedo of conventional size is sufficient to cause holing of the inner bottom in way of the contact. This results in virtually complete destruction of the machinery and the equipment in the immediate vicinity of the explosion. Excluding this type of damage, little or no shock damage to machinery is to be expected from contact explosions, except possibly in the region immediately adjacent

to the area of structural damage and in parts of the ship that undergo large low frequency oscillations due to the "whipping" of the hull that is sometimes consequent to the explosion. This has been confirmed by the analysis of many cases of torpedo damage, as mentioned in the preceding section.

Non-contact underwater explosions.—The most serious and extensive cases of shock damage to naval vessels have resulted from non-contact underwater explosions. The magnetic or acoustic mine has been the major offender, such mines usually being of large weight (500 to 2000 pounds of explosive) and being placed so as to explode at ranges of the order of 100 feet. Another source of non-contact explosions is the near-miss aerial bomb. However most near-miss bombs have exploded at relatively shallow depths, causing little shock effect as compared with similar deep explosions. A third weapon of the non-contact underwater explosion variety is the depth charge, the explosion of which may cause shock damage to the attacking ship as well as to the submarine being attacked.

Although an adequate description of the pressure phenomena that occur in the water subsequent to an underwater explosion is beyond the scope of this paper, a brief description of the generated pressure wave is necessary for a proper understanding of shock effects. The detonation of the explosive charge and the consequent initial expansion of the gas globe produces a pressure in the water of the shape shown in Figure 1. The front is very steep, an almost instantaneous rise in pressure to a maximum. This is followed by an approximately exponential fall in pressure to zero (i. e., hydrostatic), after which the pressure drops slightly below zero and then returns. The duration of the initial pulse is of the order of several milliseconds, depending upon the charge weight. This pressure wave is propagated outward from the center of the explosion at a velocity approximately equal to the speed of sound in sea water (4930 feet per second), the pressure diminishing as the wave moves outward, inversely with the first power of the distance. After the initial expansion, the gas globe oscillates, alternately contracting and expanding. At the same time the globe is rising due to its buoyancy, and soon breaks the surface, and thereby produces the last phase of the surface disturbance.

Figure 2 is a simplified diagram of the radial distribution of pressure in the water. Note that the initial pulse has the same

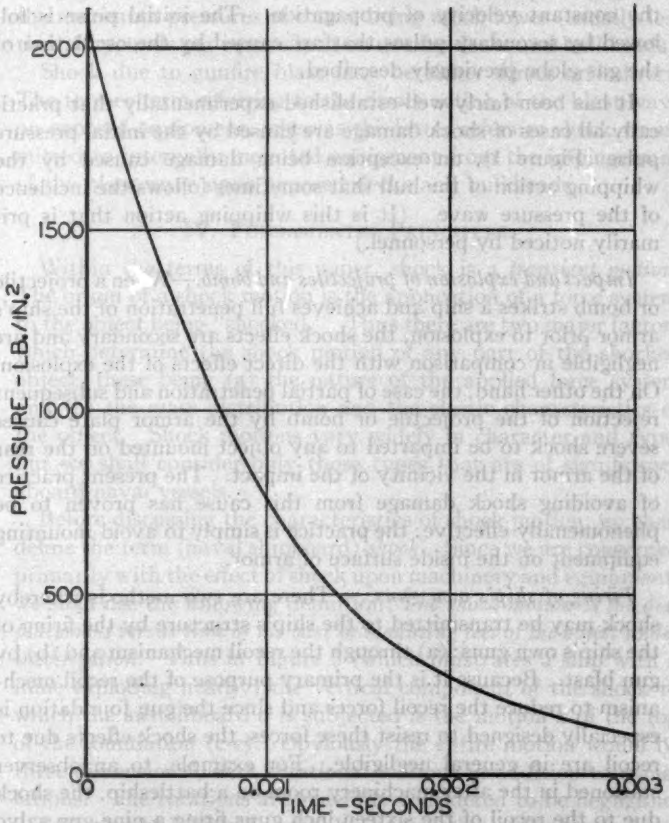

FIGURE 1—Pressure-time curve as measured in the water at a distance from a typical underwater explosion. (The high frequency pressure components are not shown.)

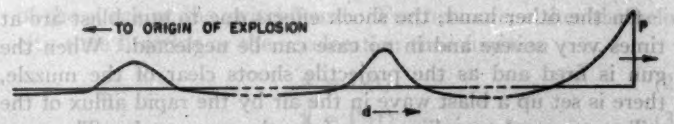

FIGURE 2—Pressure in the water one or more seconds after the explosion, which occurred at a point to the left. The negative pressures are considerably exaggerated, and the dotted lines indicate a condensation of the distance scale (d).

shape as the pressure-time curve of Figure 1, this being due to the constant velocity of propagation. The initial pulse is followed by secondary pulses that are caused by the oscillation of the gas globe previously described.

It has been fairly well-established experimentally that practically all cases of shock damage are caused by the initial pressure pulse (Figure 1), an exception being damage caused by the whipping action of the hull that sometimes follows the incidence of the pressure wave. (It is this whipping action that is primarily noticed by personnel.)

Impact and explosion of projectiles and bomb.—When a projectile or bomb strikes a ship and achieves full penetration of the ship's armor prior to explosion, the shock effects are secondary and are negligible in comparison with the direct effects of the explosion. On the other hand, the case of partial penetration and subsequent rejection of the projectile or bomb by the armor plate causes severe shock to be imparted to any object mounted on the rear of the armor in the vicinity of the impact. The present practice of avoiding shock damage from this cause has proven to be phenomenally effective: the practice is simply to avoid mounting equipment on the inside surface of armor.

Firing of ship's own guns. — There are two methods whereby shock may be transmitted to the ship's structure by the firing of the ship's own guns: (a) through the recoil mechanism and (b) by gun blast. Because it is the primary purpose of the recoil mechanism to reduce the recoil forces and since the gun foundation is especially designed to resist these forces, the shock effects due to recoil are in general negligible. For example, to an observer stationed in the after machinery room on a battleship, the shock due to the recoil of the sixteen inch guns firing a nine-gun salvo is felt as a definite although slight jar, accompanied by a sudden horizontal motion of the machinery platform of the order of 1/16 inch.

On the other hand, the shock effects due to gun blast are at times very severe and in no case can be neglected. When the gun is fired and as the projectile shoots clear of the muzzle, there is set up a blast wave in the air by the rapid afflux of the still compressed propelling gases from the gun muzzle. The wave is propagated outward at a high initial velocity which soon falls to approximately the acoustic velocity. In shape, the wave is

steep-fronted and the simpler forms have the shape of Figure 1, the maximum pressures of course being much lower (usually less than 10 pounds per square inch on nearby decks and bulkheads).

Shock due to gunfire blast may be either direct or indirect. The former term referring to the direct action of the blast wave on exposed equipment, whereas the latter refers to shock transmitted to internally mounted equipment from the impingement of the blast wave upon exposed decks and bulkheads.

IV. Fundamental Principles.

Within the terms of this paper, shock is a *transient motion*. The origin of a shock motion is the application of a force system to the object being "shocked." Thus there are two major factors which determine the shock motion of any part of the shocked object, these being (a) the nature of the applied force system and (b) the mass distribution and the elastic characteristics of the object. Shock motions vary widely in character and type, but we shall consider only those types that are of significance aboard naval vessels.

Before discussing the characteristics of shock motion, we shall define the term (naval shipboard) *shock*. Since we are concerned primarily with the effect of shock upon machinery and equipment, we shall use the following definition: ***The shock motion is the displacement versus time of the base or mounting feet of the object under investigation.*** Thus in Figure 3 (which illustrates a ship with a mine exploding nearby) the vertical component of the shock to which the switchboard a is subjected is the motion x of the top of the foundation (c-c). Obviously the entire motion would be three-dimensional, with rotational motions in addition to translations. The rotations are generally considered to be negligible.

Referring to Figure 3, a graph or a function of the motion x

$$x = f(t) \tag{1}$$

would then be a complete description of the vertical component of the shock at the switchboard. Furthermore, either the velocity-time function or the acceleration-time function

$$\dot{x} = f'(t) \tag{2}$$

$$\ddot{x} = f''(t) \tag{3}$$

would also be a complete description of shock, since by integration (1) may be obtained from (2) or from (3). (However, in

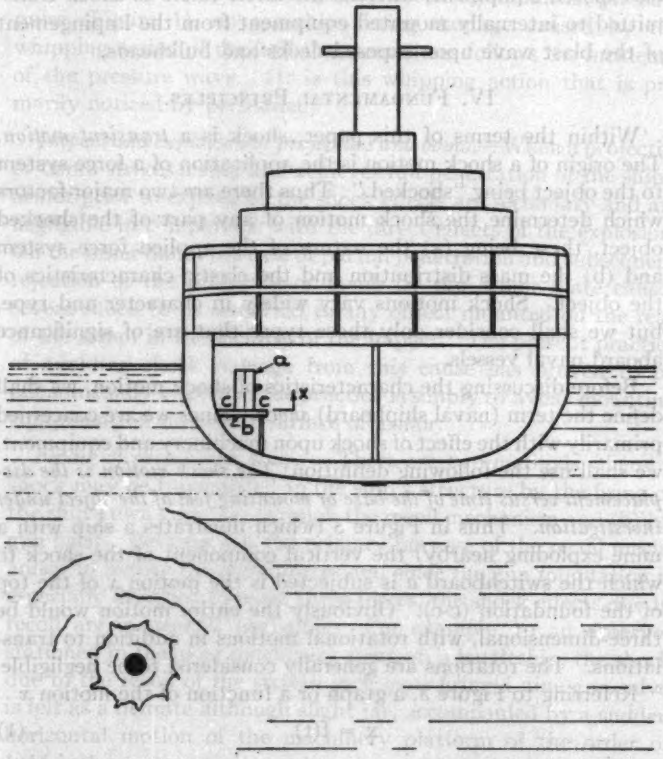

FIGURE 3—Cross-section of a ship at a machinery compartment.

practical measurements, the processes of integration and differentiation are severely limited in application because of measurement errors.)

The data from the few full-scale tests on ships that have been conducted indicate that the present type and intensity of shock as delivered by the high impact shock testing machines now in use are in reasonable accordance with the most severe shock that may be experienced aboard ship. In Figure 4(a) is illustrated the shock motion as measured on a shock machine. Shown also in Figure 4 are the velocity-time and acceleration-time records as obtained by differentiation of the displacement curve. It is considered that this shock motion is applicable as a test to items mounted on a stiff foundation relatively close to the bottom or the sides of the ship. In contrast, items mounted on decks and bulkheads exposed to the direct action of gun blast shock may be subjected to shock that is more vibratory in character, as shown in Figure 5.

In Figure 6 is shown a machine M which is subjected to a shock motion x. Shown also is a free body diagram of the machine, assumed to be symmetrical. Consider that the upward motion x consists of an acceleration $\ddot{x}$ (Figure 6(a)). Then from Newton's Law:

$$\frac{1}{2}R + \frac{1}{2}R - W = \frac{W}{g}\ddot{x}$$

$$R = W\left(\frac{\ddot{x}}{g} + 1\right) \tag{4}$$

Where R = total reaction, W = weight of M, and g = acceleration of gravity. In shock of the type experienced on naval vessels, the maximum accelerations are large in comparison with the acceleration of gravity, so that

$$R = W\frac{\ddot{x}}{g} \tag{4.1}$$

From this equation it is seen that the acceleration $\ddot{x}$ determines the magnitude of the shock forces on the machine. Also the advantage of employing the acceleration of gravity (g) as the unit of acceleration is made apparent by equation (4.1), inasmuch as the calculation of the shock forces is thereby simplified. For example, if the acceleration is 10g, the reaction R = 10W.

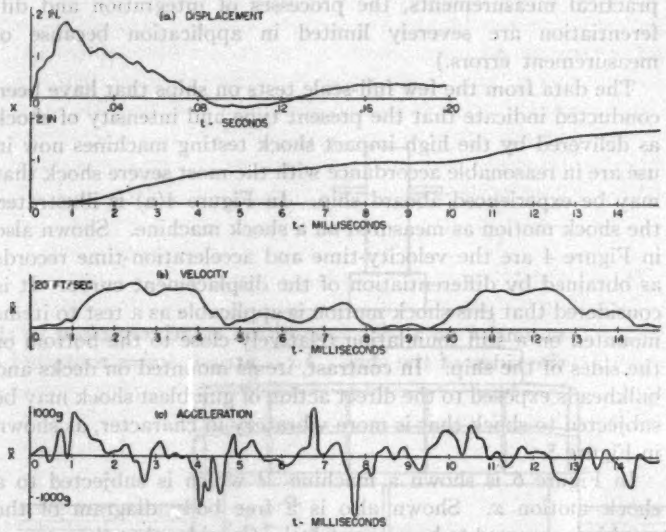

FIGURE 4—Shock displacement curves: (a) as measured on light weight high impact shock machine; and (b) and (c), derived velocity and displacement curves.

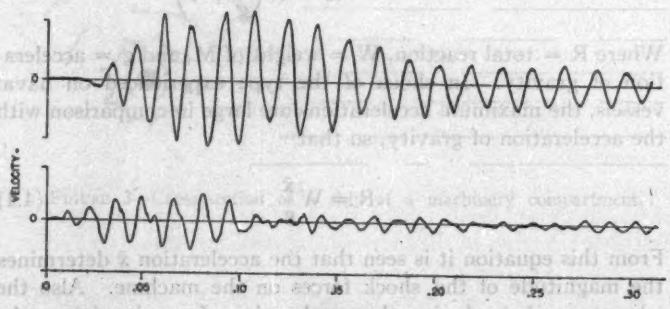

FIGURE 5—Shock motion of exposed superstructure bulkhead when subjected to muzzle blast from the ship's own guns.

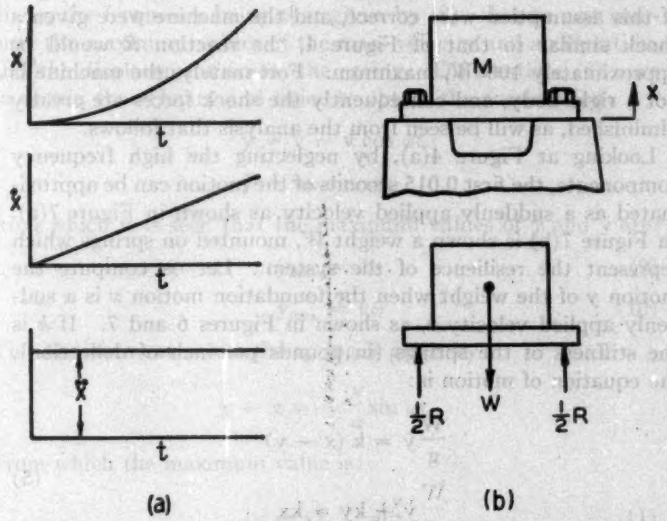

FIGURE 6—An item of equipment subjected to a steady acceleration.

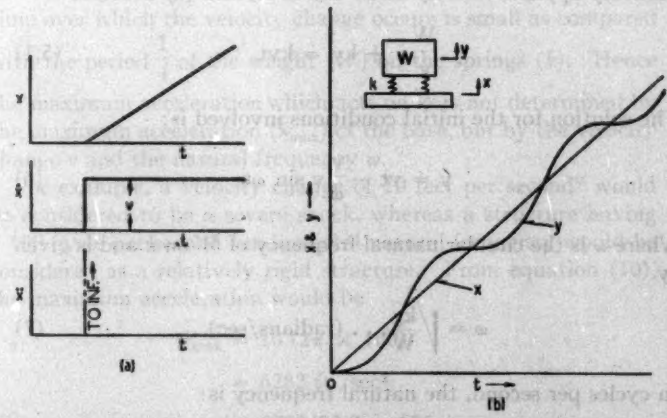

FIGURE 7—Motion (y) of a shock mounted machine when the foundation is subjected to a sudden change in velocity.

The derivation above assumes that the machine M is rigid. If this assumption were correct, and the machine were given a shock similar to that of Figure 4, the reaction R would be approximately $1000W$, maximum. Fortunately, the machine is not a rigid body, and consequently the shock forces are greatly diminished, as will be seen from the analysis that follows.

Looking at Figure 4(a), by neglecting the high frequency components, the first 0.015 seconds of the motion can be approximated as a suddenly applied velocity, as shown in Figure 7(a). In Figure 7(b) is shown a weight W, mounted on springs which represent the resilience of the system. Let us compute the motion y of the weight when the foundation motion x is a suddenly applied velocity v, as shown in Figures 6 and 7. If k is the stiffness of the springs (in pounds per inch of deflection), the equation of motion is:

$$\frac{W}{g}\ddot{y} = k(x - y)$$

$$\frac{W}{g}\ddot{y} + ky = kx \tag{5}$$

The foundation is initially at rest so that before zero time $x = y = 0$ and $\dot{x} = \dot{y} = 0$. After zero time $x = vt$, v being the suddenly applied velocity and t the time, and (5) becomes:

$$\frac{W}{g}\ddot{y} + ky = kvt \tag{5.1}$$

The solution for the initial conditions involved is:

$$y = vt - \frac{v}{\omega} v \sin \omega t \tag{6}$$

Where ω is the circular natural frequency of W on k and is given by

$$\omega = \sqrt{\frac{kg}{W}} \ldots \text{(radians/sec)} \tag{7}$$

In cycles per second, the natural frequency is:

$$f = \frac{\omega}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{kg}{W}} \tag{8}$$

As shown in Figure 7, the motion y is oscillatory about the base line x, the frequency being that given by (8). Let us now compute the maximum values of the mass velocity and acceleration, and the displacement across the spring. Differentiate (6) once to obtain the velocity and twice to obtain the acceleration:

$$\dot{y} = v - v \cos \omega t$$

$$\ddot{y} = v\omega \sin \omega t$$

from which it is seen that the maximum values of $\dot{y}$ and $\ddot{y}$ are:

$$\dot{y}_{max} = 2v \tag{9}$$

$$\ddot{y}_{max} = v\omega \tag{10}$$

The displacement across the spring is given by:

$$y - x = -\frac{v}{\omega} \sin \omega t$$

From which the maximum value is:

$$(y - x)_{max} = \frac{v}{\omega} \tag{11}$$

Now it can be shown that the maximum values of (9), (10) and (11) are not appreciably affected by the rapidity with which the velocity v is applied (i. e., by the acceleration), provided the time over which the velocity change occurs is small as compared with the period $\frac{1}{f}$ of the weight (W) on the springs (k). Hence the maximum acceleration which acts on W is not determined by the maximum acceleration ($\ddot{x}_{max}$) of the base, but by the velocity change v and the natural frequency ω.

For example, a velocity change of 10 feet per second* would be considered to be a severe shock, whereas a structure having a 100 cycle per second fundamental natural frequency would be considered as a relatively rigid structure. From equation (10), the maximum acceleration would be

$$\ddot{y}_{max} = 10\,(2\pi \times 100)$$

$$= 6282 \text{ ft./sec}^2$$

$$= 6282/32.2 = 195 \text{ g}$$

* Actually, the average velocity over the first .015 second of the motion of Figure 4 may be calculated to be 9.7 ft./sec.

It is seen that this value of maximum acceleration is about 1/5 the value of 1000g as shown on Figure 4(c).

Although presented numerically, the above analysis is intended only for simple illustration, since in the actual case both the mass and the elasticity would be distributed rather than concentrated as assumed. Only in the case of shock mounted machines do actual conditions approach this idealized case.

V. Full-Scale Tests.

As mentioned in the previous section, there exists only meager data relating to shock as measured aboard ship. In the past, explosive charges have been of such size that effective maximum ranges were of the order of 100 feet. This meant that when the pressure wave impinged upon the hull, the wave was quite spherical in shape, as compared with the length of the ship. Hence the shock effect was limited in extent, affecting at most 100 feet of the ship's length. In no case of shock damage during the war, was extensive damage reported to have extended over great lengths of the ship.

However, in the case of an atomic bomb explosion, the underwater pressure wave can be expected to be of damaging intensity when the explosion occurs at ranges of many times the ship's length. Therefore, upon incidence with the hull, the wave may have so small a curvature as to be nearly a plane wave. Hence it is possible that shock damage may extend throughout the ship, and this effect may thereby negate the safety now inherent in the separation of the propulsion plants and the electric plants along the length of the ship.

VI. Shock Testing Machines.

The current standards* for shockproof equipment require that tests be conducted on machines referred to as "high impact shock testing machines." During the shock tests, the equipment is tested in each of its several operating conditions, and either maloperation or damage is considered as failure to pass the test. Furthermore, because of the severity of the shock, the test is assumed to be destructive, so that the tested sample is deemed unfit for shipboard use and is discarded.

In 1941, the high impact (Class H.I.) shock testing machines

* See Navy Dept. Specification 66S3: "Shockproof Equipment, Class H.I. (High Impact); and Tests for."

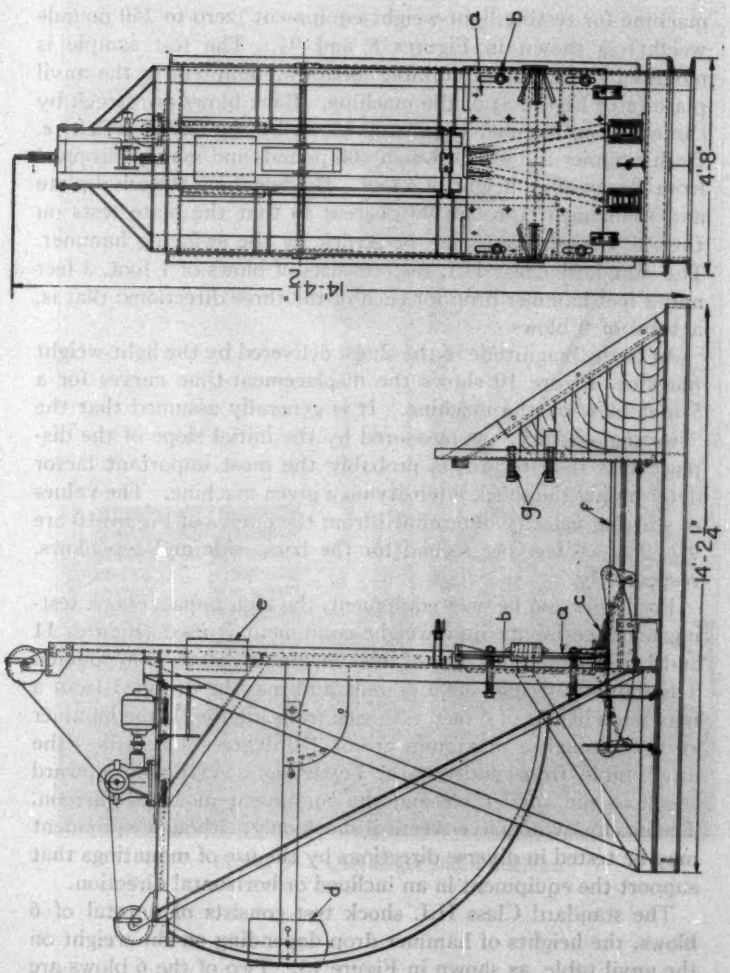

FIGURE 8—High impact shock testing machine for light-weight equipment.

were adopted as the standard machine for the shock test of electrical power and lighting equipment, and since then their use has been extended to many other classes of equipment. The machine for testing light-weight equipment (zero to 250 pounds weight) is shown in Figures 8 and 9†. The test sample is mounted by means of suitable mounting adapters to the anvil plate (*a* of Figure 8) of the machine. Back blows are struck by the swinging hammer *d* and top blows by the falling weight *e*. Both hammer and weight weigh 400 pounds and may be dropped from a maximum height of 5 feet. By detaching the anvil plate and swinging it through 90 degrees so that the plate rests on the rail *f*, side blows may be struck by the swinging hammer. The standard Class H.I. test consists of blows of 1 foot, 3 feet and 5 feet hammer drop for each of the three directions: that is, a total of 9 blows.

As to the magnitude of the shock delivered by the light-weight machine, Figure 10 shows the displacement-time curves for a 5 foot blow on the machine. It is generally assumed that the "starting velocity," as measured by the initial slope of the displacement-time record, is probably the most important factor determining the shock intensity on a given machine. The values of starting velocity determined from the curves of Figure 10 are 9.2, 9.6, 7.8 feet per second for the back, side and top blows, respectively.

For larger and heavier equipment, the high impact shock testing machine for medium-weight equipment is used (Figures 11 and 12). The weight range of this machine is 250 to 4500 pounds. The hammer weighs 3000 pounds and may be dropped from a maximum height of 6 feet. As seen from Figure 11, the hammer swings through a maximum arc of 270 degrees and strikes the anvil table from underneath, imparting a vertically upward shock to the anvil table and the equipment mounted thereon. The machine can deliver vertical shock only, although equipment may be tested in diverse directions by the use of mountings that support the equipment in an inclined or horizontal direction.

The standard Class H.I. shock test consists of a total of 6 blows, the heights of hammer drop depending on the weight on the anvil table, as shown in Figure 13. Two of the 6 blows are taken from Curve I and four of the blows from the curve marked "II & III." The characteristics of the shock delivered are

† This machine is similar to a machine developed by the British Admiralty in 1940.

FIGURE 9—Light-weight shock machine.

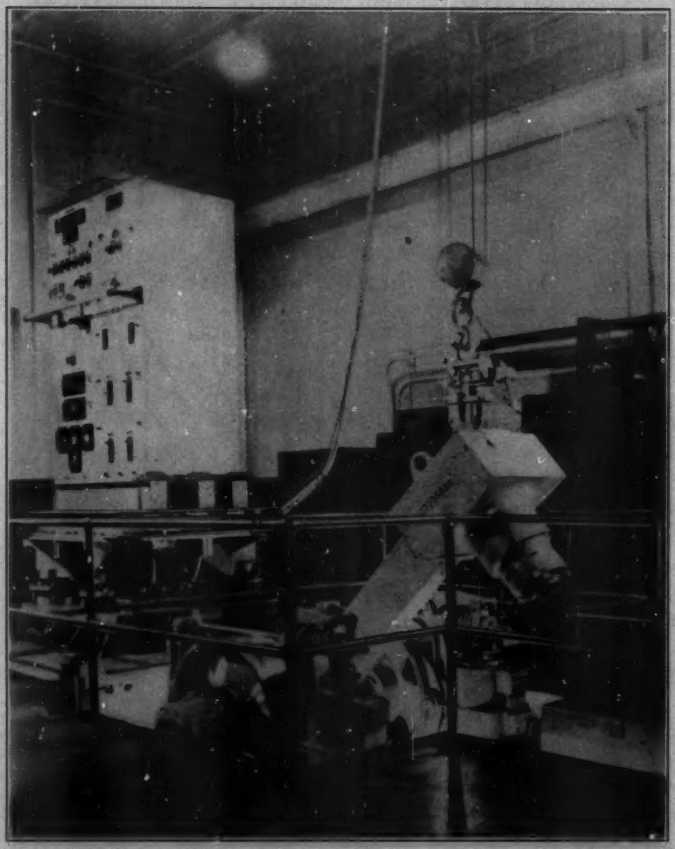

FIGURE 12—Medium-weight shock machine, showing a control switchboard mounted for test.

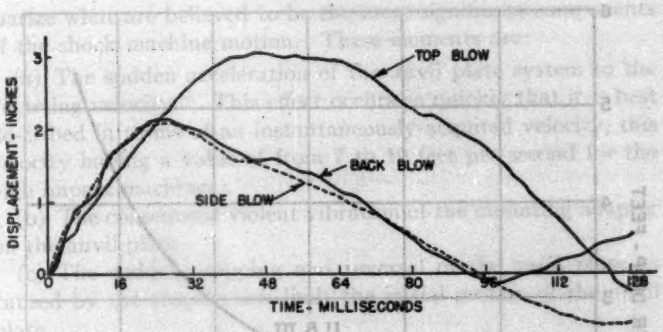

FIGURE 10—Displacement-time records of anvil plate of light-weight shock machine, for 5 foot hammer blows. The curves for the side and top blows were taken directly on the anvil plate, whereas that for the back blow was taken at the center of the mounting adapter plate.

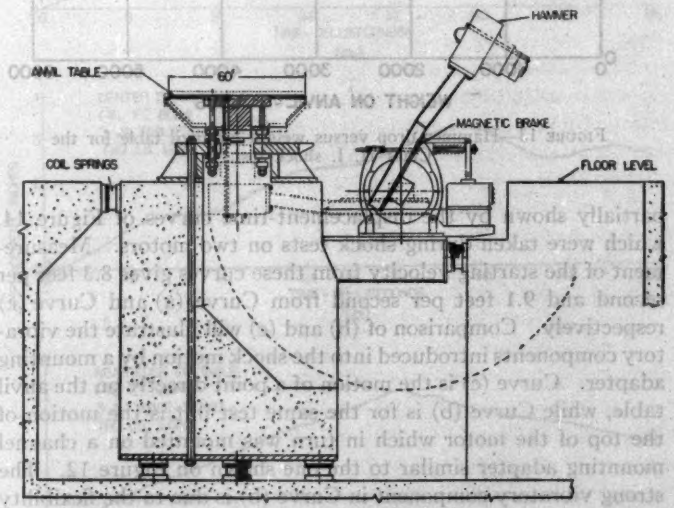

FIGURE 11—High impact shock testing machine for medium-weight equipment.

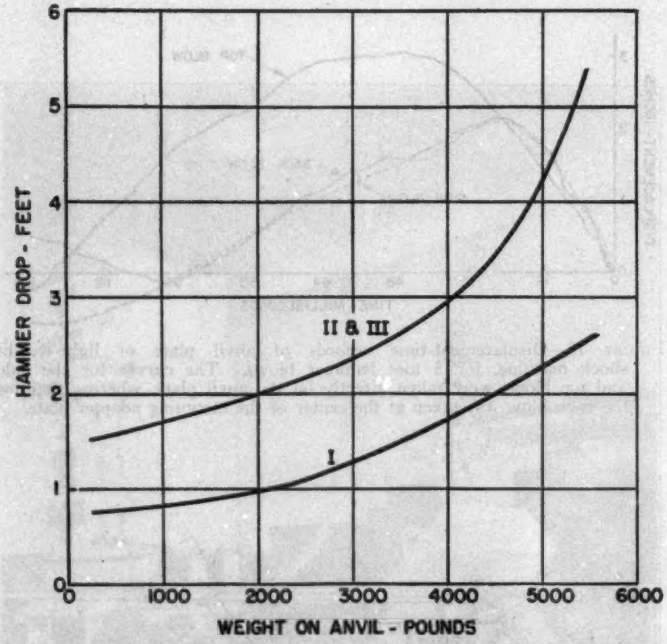

FIGURE 13—Hammer drop versus weight on anvil table for the Class H. I. shock test.

partially shown by the displacement-time curves of Figure 14, which were taken during shock tests on two motors. Measurement of the starting velocity from these curves gives 8.3 feet per second and 9.1 feet per second from Curve (a) and Curve (c) respectively. Comparison of (b) and (c) will illustrate the vibratory components introduced into the shock motion by a mounting adapter. Curve (c) is the motion of a point directly on the anvil table, while Curve (b) is for the same test but is the motion of the top of the motor which in turn was mounted on a channel mounting adapter similar to the one shown on Figure 12. The strong vibratory component in Curve (b) is due to the flexibility of the mounting adapter, the frequency of the vibration being determined by the ratio of the flexibility to the weight of the motor under test.

Considering all high impact shock machines, we may sum-

marize what are believed to be the most significant components of the shock machine motion. These elements are:

(a) The sudden acceleration of the anvil plate system to the "starting velocity." This effect occurs so quickly that it is best described in terms of an instantaneously-acquired velocity, this velocity having a value of from 7 to 10 feet per second for the high impact machines.

(b) The consequent violent vibration of the mounting adapter on the anvil plate.

(c) The sudden stopping and reversal of the anvil plate as caused by the stops which limit the initial motion of the anvil plate.

Now with respect to the correlation of the shock machine motion with shipboard shock motions as measured during full

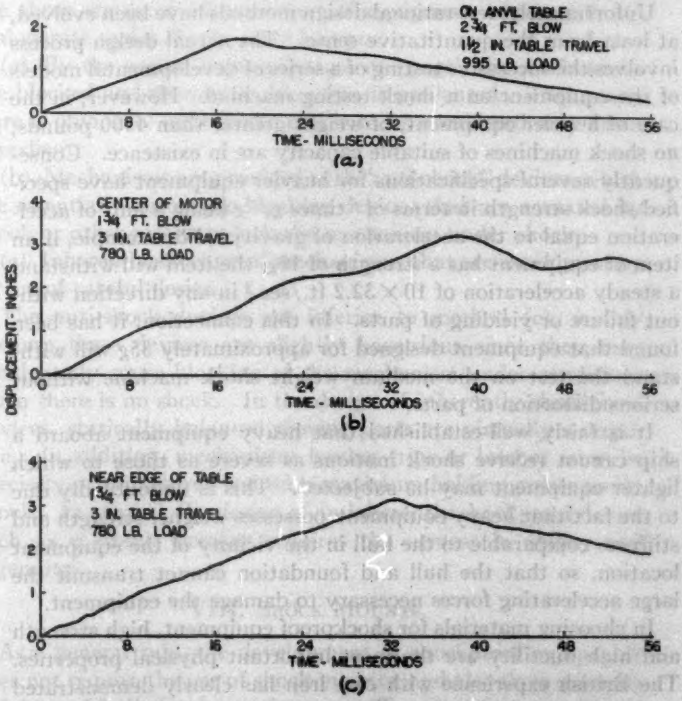

FIGURE 14—Displacement-time records of medium-weight shock machine.

scale tests, it may be said that the suddenly-acquired shock velocities measured aboard ship under severe shock conditions are of the order of 10 feet per second, so that it is believed that the machines simulate shipboard shock intensity to the extent of (a) at least. Insofar as (b) is concerned, qualitative effort is exerted to insure that the mounting adapter used for test partially simulates the mounting structure employed in the shipboard installation of the equipment.

VII. Design of Shockproof Equipment.

Equipment design problems are divided into two classes, those relating to damage under shock and those relating to the maloperation of the equipment under shock. The first class of problems properly is a part of strength of materials, the second being essentially that of mechanisms.

Unfortunately, few rational design methods have been evolved, at least from the quantitative sense. The actual design process involves the successive testing of a series of developmental models of the equipment on a shock testing machine. However, in the case of heavier equipment, of weight greater than 4500 pounds, no shock machines of suitable capacity are in existence. Consequently several specifications for heavier equipment have specified shock strength in terms of "times g," g being a unit of acceleration equal to the acceleration of gravity. For example, if an item of equipment has a strength of $10g$, the item will withstand a steady acceleration of 10×32.2 ft./sec.^{2} in any direction without failure or yielding of parts. In this connection, it has been found that equipment designed for approximately $35g$ will withstand the test on the medium weight shock machine without serious distortion of parts.

It is fairly well-established that heavy equipment aboard a ship cannot receive shock motions as severe as those to which lighter equipment may be subjected. This is undoubtedly due to the fact that heavy equipment possesses weight, strength and stiffness comparable to the hull in the vicinity of the equipment location, so that the hull and foundation cannot transmit the large accelerating forces necessary to damage the equipment.

In choosing materials for shockproof equipment, high strength and high ductility are the most important physical properties. The British experience with cast iron has clearly demonstrated that the use of this brittle material should not be tolerated. Glass

and porcelain should be avoided where possible, and high strength plastics should be used in preference to the more common types. In the design of parts, great care should be exercised to minimize stress concentrations as caused by notches and sharp, re-entrant corners.

In assemblies, joints should be given especial attention. Welded or brazed joints are generally satisfactory, because with these joints the possibility of impacting under shock is virtually eliminated. Bolted joints for parts requiring close alignment must be provided with large dowels or with fitted bolts, and in any event, the bolts should be drawn up very tight, preferably until slight yielding of the bolt occurs. Riveted joints are generally not desirable in shockproof designs.

The development of operationally shockproof equipment is not as straightforward as designing to prevent shock damage. There are three states of advancement of equipment which will not maloperate under shock, these being:

(a) By the use of locking devices or "gags" the mechanisms are blocked and thereby malfunction is prevented. This procedure is obviously undesirable and is to be considered only as an expedient.

(b) Mechanisms are provided with "anti-shock" devices, which are essentially automatic blocking devices that are actuated by shock or other means to lock the mechanism under shock.

(c) Inherently shockproof mechanisms, that are shockproof by virtue of careful design.

The anti-shock devices are inferior to method (c), mainly because these devices are slightly hazardous since they may accidentally cause blocking of the mechanism under conditions when there is no shock. In the design of inherently shockproof devices, statically balanced moving parts are virtually a requisite. In addition, mechanisms having trips or latches must be precisely manufactured to insure maximum holding power under shock. In general, the design of an inherently shockproof device such as a circuit breaker requires the utmost in ability and ingenuity.

VIII. Shock Mounts.

As a general rule, the development of shockproof equipment does not require the use of shock mounts, and also their use adds weight and bulk to the equipment. Therefore it is considered

good design practice not to use shock mounts except for existing non-shockproof equipment and for inherently delicate and fragile equipment, as for example, incandescent lamps and certain electronic devices.

A shock mount functions by virtue of the relative motion that occurs across the mount during shock. Furthermore, the efficacy of the mount is virtually proportional to the amplitude of motion across the mount. Hence, the general statement can be made that the greater the allowable motion, the better the performance of the mount.

Any shock mounting must be designed so as to avoid a resonant condition with normal shipboard vibration. Since the frequency of predominant shipboard vibration extends over the range 5 to 23 cycles per second*, the only practical way to avoid resonance is to design the shock mounting so that all natural frequencies are above 23 cycles per second. Of course, if the mounting is excessively stiff it is then ineffective as a shock mount. Usually a design frequency in the range of 25-30 cycles per second is chosen. Even this choice results in a stiff mounting, but it may be easily shown that this degree of stiffness is required to prevent bottoming of the mount under severe shock, unless deflections in excess of one inch are allowed for by design.

Referring back to Figure 7, consider W to be an item of equipment shock mounted on two springs of total stiffness k, assumed to have linear load-deflection characteristics. Now if the base is given the shock motion x (i. e., a suddenly applied velocity), the motion of W will be as shown by the curve y and Equation (6). The maximum acceleration of W and the maximum spring deflection are given by Equations (10) and (11).

$$\ddot{y}_{max} = v\omega \qquad (10)$$

$$(y - x)_{max} = \frac{v}{\omega} \qquad (11)$$

where v is the suddenly-acquired velocity of the foundation and

$$\omega = \sqrt{\frac{k}{W/g}}.$$

As an example, if $v = 10$ feet per second and the natural fre-

* The ship's propellers are the primary excitation source of shipboard vibration, the fundamental frequency being the blade frequency (i. e., shaft R.p.m. times number of blades per propeller). Considering all classes of fleet vessels and their speed ranges, this frequency may range from 5 to 23 cycles per second.

quency of W on k is 25 cycles per second, so that $\omega = 2\pi \times 25$,

$$\ddot{y}_{max} = 49g$$

$$(y - x)_{max} = 0.76 \text{ inch}$$

In actual shock mounts, the load-deflection curves are not linear* and this usually results in an increase in $\ddot{y}_{max}$ and a decrease in $(y - x)_{max}$.

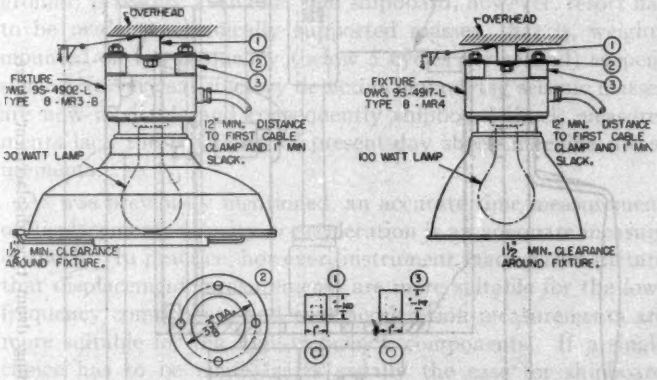

FIGURE 15—Steel shock mounting for 100 watt reflector fixtures.

For elastic mounts, rubber is the usual resilient element. However, there is a class of mounts that employs deformable mild steel springs, and these mounts have proven to be excellent for cases where permanent yielding of the mount is permissible. Figure 15 shows an annular plate mount that has proven satisfactory for lamps and fixtures. Furthermore, on submarines the use of simple one-half inch thick felt washer mounts has afforded some protection for gages, meters and lamps. However, the felt is not very serviceable in that it is subject to creep and hardening with age.

For design and application procedures for elastic shock mounts the reader is referred to Bureau of Ships Publication Navships 250-600, "Shock Mounts for Naval Shipboard Service."

* For a complete analytical discussion of non-linear systems subjected to a sudden velocity change, see the article "Dynamics of Package Cushioning," R. D. Mindlin, The Bell System Technical Journal, v. 24, n. 3-4, July-August, 1945.

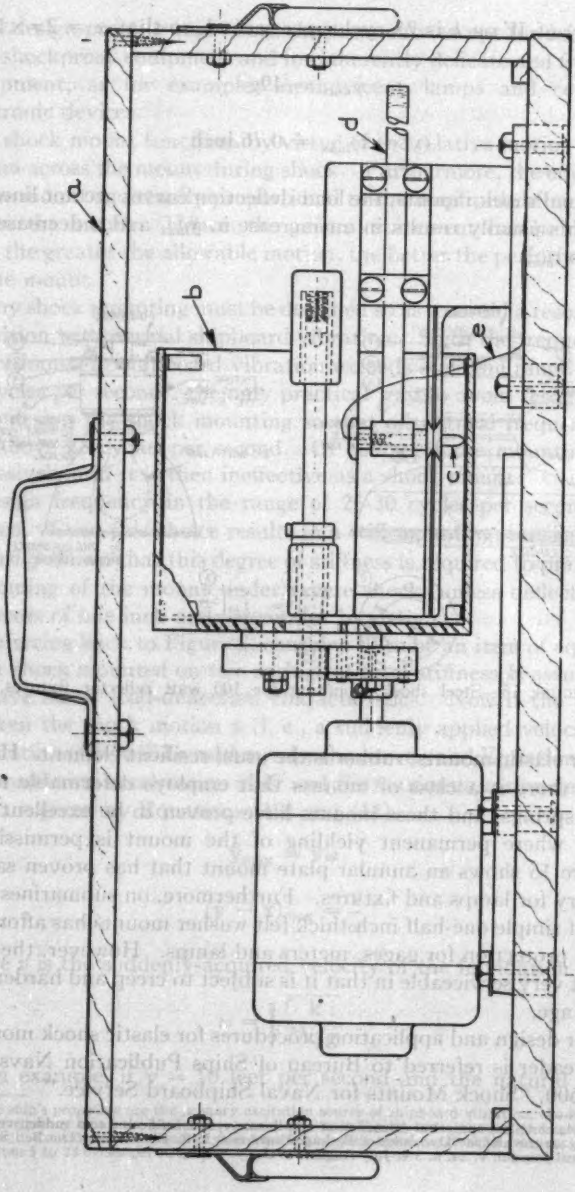

FIGURE 16—Rotating drum type displacement meter.

IX. Shock Instruments.

The problem of measuring shock is essentially that of measuring a high-speed transient motion having maximum acceleration and frequency components of the order of 1000g and 1000 cycles per second, respectively, and maximum displacements that may be as large as 3 inches. Whereas the problem is reasonably well-solved for shock machine measurements, such is not the case for measurements made aboard ships. The essential difference is that in the former case a stationary point of reference (i. e., the ground) is readily available. On shipboard, however, resort has to be made to seismically supported masses, that is, weights mounted on low-frequency (below 5 cycles per second) suspensions. No very satisfactory detectors embodying seismic masses are now available and consequently shipboard shock measurements lack the reliability of present-day shock machine measusements.

As was previously mentioned, an accurate time measurement of displacement, velocity *or* acceleration is an adequate measure of shock. In practice, however, instrument inaccuracies dictate that displacement measurements are more suitable for the low-frequency components and that acceleration measurements are more suitable for the high-frequency components. If a single choice has to be made, as is usually the case for shipboard measurements, velocity-time records appear to be the most logical selection.

Of the several displacement meters that have been developed, the rotating-drum mechanical meter has proven to be one of the most satisfactory. Figure 16 is a sketch of one model, with the carrying case *a* in place. Recording is by a rounded-point stylus *c* on carbon-backed paper which is held by centrifugal force on the inner surface of the rotating drum *b*. The stylus is driven directly by the drive-rod *d* which in turn is connected to the point of measurement through two ball-and-socket joints. The base of the instrument must be mounted on a stationery platform. The displacement scale on the record is 1:1 and the time scale is 0.004 second per inch, as shown by the typical records of Figure 17 which were taken on the light-weight shock machine.

The measurement of displacement by streak photography, developed by the Taylor Model Basin, is a very precise method

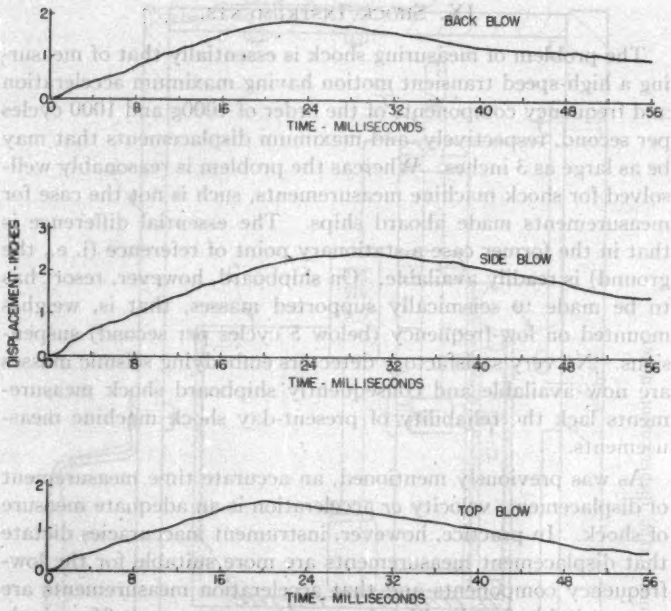

FIGURE 17—Displacement-time records of modified light-weight shock machine. Records taken on anvil plate.

having a high resolving power.* A moving-film camera photographs a point source of light moving normal to the camera optic axis and the direction of film motion, so that a displacement-time record of high accuracy is obtained on the film.

For motion studies of equipment, as well as for fundamental shock studies, the high speed motion picture camera has proven invaluable. In fact, it may be categorically stated that the high-speed movie camera is the most valuable single instrument for equipment development. The camera found to be the most useful is the type with a rotating-prism shutter and continuously moving film. Constant illumination of subject is employed. A frame speed of about 2000 frames per second is satisfactory for the usual shock problem. The Eastman Type III camera has proven to be the most convenient model for routine experiments.

For shipboard shock measurements a velocity meter of English design has been the instrument most extensively employed. It

* See Naval Research Laboratory Report No. 0-2645.

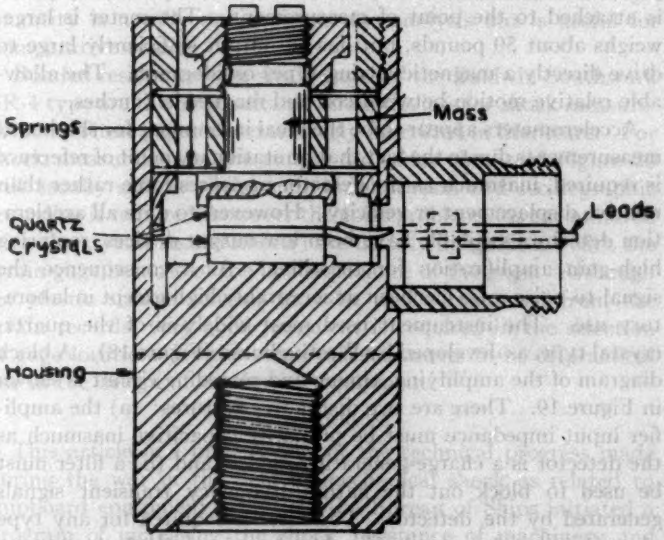

FIGURE 18—Westinghouse quartz crystal accelerometer. (Approximately full size)

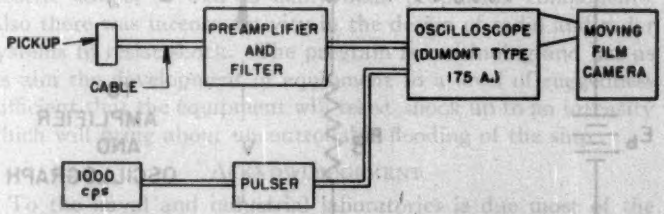

FIGURE 19—Block diagram of accelerometer recording circuit.

consists of a d-c electro-magnet, seismically supported, which produces a radial field in a cylindrical air-gap: the signal is generated by a cylindrical coil which moves in the air gap and is attached to the point of measurement. The meter is large, weighs about 50 pounds, but has an output sufficiently large to drive directly a magnetic (string-type) oscillograph. The allowable relative motion between coil and magnet is 2 inches.

Accelerometers appear to be the ideal instrument for shipboard measurements due to the fact that no stationary point of reference is required, inasmuch as the detector measures force rather than relative displacement or velocity. However, to date all acceleration detectors available have been low-output devices, requiring high-gain amplification for recording. As a consequence the signal-to-noise ratio has been unacceptably high except in laboratory use. The instrument used most widely is of the quartz-crystal type, as developed by Westinghouse (Figure 18). A block diagram of the amplifying, timing and recording circuit is shown in Figure 19. There are two distinctive features: (a) the amplifier input impedance must be primarily capacitive inasmuch as the detector is a charge-generating device, and (b) a filter must be used to block out the natural-frequency transient signals generated by the detector. The filter is required for any type of acceleration detector having low damping. With the quartz-crystal detector, a 5000 cycle per second low-pass filter having almost aperiodic damping is usually employed.

A variety of simple indicating gages have been proposed or

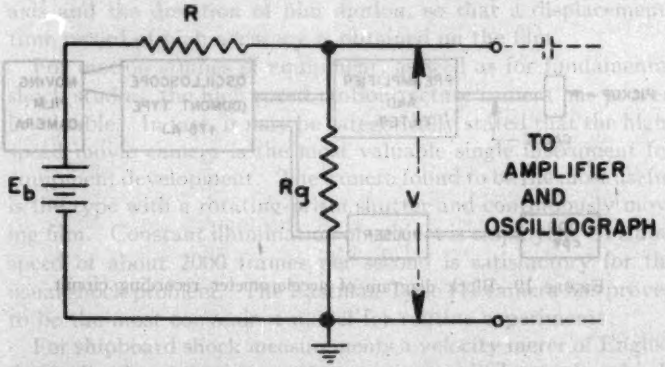

FIGURE 20—Series circuit for resistance wire strain gage. R = series resistor; E_b = battery voltage; R_g = strain gage.

used for measuring shock. The quantities measured are usually peak acceleration or relative displacement. However, because of the complexity of shock motions, the indication of a single quantity is usually not sufficient for analysis but is useful for comparative results.

Bonded resistance-wire strain gages of the Baldwin-Southwark SR-4 type are the most suitable strain devices for shock measurements. These gages are extensively described in literature. For shock measurements, the simple d-c series circuit of Figure 20 will usually suffice. High-gain amplification and oscillographic recording is required; however the noise problems (as encountered with the crystal accelerometer) are usually insignificant with the strain gage because of the low impedance of the gage. Although for elastic strains stresses may be easily computed from the strain records, very good judgment is required in the selection of gage locations for the stress measurements to be of practical use in the design of shockproof equipment.

Conclusion.

This article is a brief review of the technical progress made during the war in the field of mechanical shock as related to shipboard equipment. In 1941 the Bureau of Ships initiated a program of increasing the shock resistance of machinery and equipment. A new and intensified shock test, the Class H.I. shock test, was introduced and made standard. Many items of equipment were redesigned to this new standard. Included were virtually all components of the electric power systems, from the generators through the switchboards to the motors and the electric lamps, as well as many main propulsion components. Also there was intense activity in the design of radio and radar systems to resist shock. The program is continuing and has as its aim the development of equipment to a level of ruggedness sufficient that the equipment will resist shock up to an intensity which will bring about uncontrollable flooding of the ship.

Acknowledgement.

To the naval and industrial laboratories is due most of the credit for technical advancement in this field. These agencies include the Naval Research Laboratory, the Taylor Model Basin, the Material Laboratory, the Naval Engineering Experiment Station, the Westinghouse Research Laboratories and the General Electric Laboratories.

NOTES.

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A LIQUID-PROPELLANT ROCKET MOTOR.
—Mechanical Engineering, July, 1946.

THE MECHANISM OF THE GERMAN ROCKET BOMB ("V2").
—Journal and Proceedings of the Institution of Mechanical Engineers, June, 1946.

ROCKETS.
—Product Engineering, July, 1946.

JET PROPULSION ENGINES AND PROPELLER DRIVE GAS TURBINES—THEIR APPLICATION IN FUTURE AVIATION.
—Journal of the Franklin Institute, March, 1946.

Because of the increasing interest of the Navy in guided missiles, rockets, and jet propulsion in general, a number of articles on this subject are reproduced in the following pages from various publications. There is some repetition of material between the papers, but the group as a whole, if read in the order printed, should give one a basic knowledge of the science as it stands today; and with a little imagination one can project in his own mind, what the future holds.

The first article is just what the title implies; it sets forth the fundamental principles of rocket and jet propulsion and acquaints one with the more common terms.

The second article discusses briefly a simplified type of liquid-propellant rocket motor and goes into some detail on the subject of efficiencies of rocket propulsion versus the conventional type of reciprocating engine propeller propulsion.

The third article describes in considerable detail the construction of the German Rocket Bomb (V-2).

The fourth article outlines the work now underway at White Sands, New Mexico in rocket research. It repeats briefly some of the descriptive work covered by the previous paper and describes the American WAC Corporal.

The fifth article dwells more on the various types of jet propulsion engines developed for aircraft. It describes some of the engines which have been developed in this country and their application to aircraft propulsion.

AN INTRODUCTION TO ROCKETS AND JET PROPULSION.*

By G. Edward Pendray.

SECRETARY, THE AMERICAN ROCKET SOCIETY AND INDUSTRIAL PUBLIC RELATIONS COUNSELLOR.

Jet propulsion is a method of developing thrust or push by ejecting a stream or jet of gas or other matter at high velocity. It will thus be seen that jet propulsion is the name of a general principle of propulsion, which may be applied to the driving of any suitable vehicle. We might imagine almost an infinite variety of such vehicles, moving through air, water, or space. The squid, for example, is an underwater vehicle driven by jet propulsion. Being a kind of fish which long antedated man on this globe, the squid, can therefore probably establish a satisfactory claim to the invention of jet propulsion, having been using it successfully now for more than 10,000,000 years.

In the matter of air and space vehicles, we can discern two broad types which are usually known as jet planes and rockets. This brings us to two more definitions which, while simple and obvious, may nevertheless help to further clarify some of the word-produced confusion on this subject. A jet plane is an "aircraft," either with or without pilot, which is driven by jet propulsion. A rocket is a "projectile" driven by jet propulsion. Thus, we may see that a jet plane, like an ordinary aircraft, depends for support in flight on the interaction of the air and its wings. It cannot fly except through air, and depends on that air for its support.

A rocket, on the other hand, is a projectile, and thus is not in any way dependent on the air for support; in fact the air impedes it. It is supported in flight entirely by its kinetic energy or momentum, and follows a trajectory which in no way is dependent on the air, though of course it may be altered or shortened by the resistance of the atmosphere.

The jet plane and the rocket are therefore two quite different kinds of vehicles with one thing in common, both are driven by jet propulsion. The kinds of motors or engines that drive them may be, and in some cases are, identical; though in actual practice it is customary to use a continuous-power engine of the air-jet variety to drive aircraft, and a high-power rocket motor to drive a rocket.

The Rocket Motor.

Let us consider the internal construction and the operation of the simplest and best known of all the jet-propelled devices, i.e., the ordinary skyrocket, Fig. 1. At the top will be noted a cone-shaped hat, filled with black pellets. These are the "pay load" of the skyrocket, for they are the fiery stars which the rocket will eject at the top of its flight, to give the familiar pyrotechnic effect.

The stars, of course, have nothing to do with propelling the rocket. This is accomplished by the material in the cylindrical portion of the rocket just below. The outer case is usually made by soaking pasteboard in glue and water, then rolling it on a mandrel to give it the cylindrical form. Before the material hardens, the lower part is drawn in to provide a crude nozzle.

Now, when the rocket is charged (which must be done, of course, before the "star" compartment is put on) a cone-shaped dibble is driven up through the nozzle, and black gunpowder or a similar propellant mixture is packed in all around it, driven hard with the aid of a mallet or hydraulic press. When the dibble is withdrawn, a cone-shaped cavity remains in the lower part of the charge, a cavity which is sometimes picturesquely referred to as the "soul" of the rocket. The fuse, leading in from the outside, ends in this cavity.

When a skyrocket is fired, the sequence of events is as follows: The spark follows the fuse into the cavity, and ignites the walls of the powder charge. Though the charge usually consists of gunpowder, an explosion does not occur because the charge is so tightly packed the flame cannot permeate it, and can only burn therefore on the walls of the cavity. As it burns the cavity enlarges

* Reproduced from "Mechanical Engineering"—July 1946.

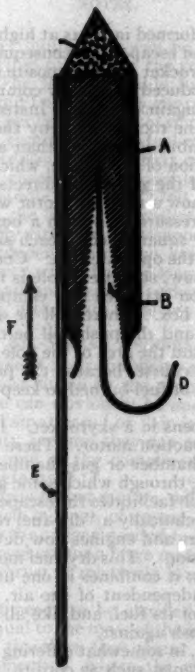


FIG. 1 CROSS SECTION OF A SKYROCKET

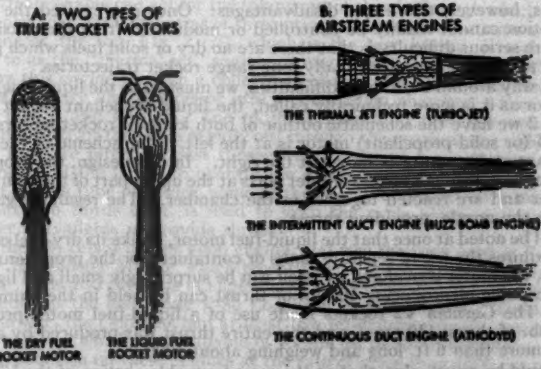

A: TWO TYPES OF TRUE ROCKET MOTORS
B: THREE TYPES OF AIRSTREAM ENGINES
THE THERMAL JET ENGINE (TURBO-JET)
THE INTERMITTENT DUCT ENGINE (BUZZ BOMB ENGINE)
THE CONTINUOUS DUCT ENGINE (ATHODYD)
THE DRY FUEL ROCKET MOTOR
THE LIQUID FUEL ROCKET MOTOR

FIG. 2 SCHEMATIC REPRESENTATION OF THE FIVE TYPES OF REACTION MOTORS

rapidly, and the fuel is transformed into gas at high temperature and pressure. There is only one place it can escape, and consequently a jet goes roaring out of the nozzle, thrusting the rocket in the opposite direction.

Now this thrust is not produced, as is very commonly but erroneously supposed, by pressure of the jet against the air. Instead, it is produced by a state of unbalanced pressures in the rocket, whereby there is more gas pressure on the forward part of the combustion cavity than at the rear. The thrust is further enhanced by the action of the nozzle, which increases the velocity of ejection, facilitates escape of the gases, and directs the flow.

We can more readily see how a reaction motor works by imagining a closed box containing gas under pressure. In such a box, according to the laws of gases, the pressure on every square inch of each side will be exactly counterbalanced by the pressure on the opposite side. Consequently, there will be no tendency to motion. But now, suppose a hole is made in one side. The gas that would have pressed upon that area now escapes, and there is no longer a condition of balance in the box. There will be a tendency to move in the direction opposite the hole, and the push will be roughly proportional to the product of the gas pressure and the area of the hole. In such a box the action would not long continue, of course, because the pressure would rapidly fall. But if new gas is brought in, or fuel burned to keep up the pressure, the action will continue.

This is exactly what happens in a skyrocket. In such a rocket, we see all of the parts essential to a reaction motor. These parts are three in number: namely, (1) a combustion chamber or gas chamber where there is gas under pressure, (2) a hole or orifice through which some gas can escape in a directed stream, and (3) a nozzle which facilitates the escape of the gas at high velocity.

The skyrocket motor is technically a "dry-fuel rocket motor." It is one of the five basic types of motors and engines now developed which work on the broad principle of jet propulsion. This dry-fuel motor is simple and ingenious. It contains no moving parts; it combines in one unit the fuel supply and the engine. It is completely independent of the air, since it needs no external oxygen for the combustion of its fuel, and like all jet-propulsion engines and motors, it needs no air to push against.

The dry-fuel rocket motor, in somewhat differing arrangement and of course using more powerful propellants, such as cordite, is the type that drives the bazooka rocket, the anti-aircraft rocket, the airplane rocket, the rockets used in amphibious landings, and the like. In fact, virtually all relatively short-range military rockets employ the dry-fuel motor because of its simplicity, compactness, and freedom from the need for field adjustment or charging.

It has, however, two major disadvantages: Once it is ignited the rate of combustion cannot readily be controlled or modulated from the outside. A still more serious difficulty is that there are no dry or solid fuels which provide enough propulsive power for really long-range rocket trajectories.

For a way around both these difficulties, we must go to the liquid-fuel rocket motor, or as it is more technically called, the liquid-propellant rocket motor. In Fig. 2 we have the schematic outline of both kinds of rocket motors. The dry-fuel (or solid-propellant) motor is at the left. The scheme of the liquid-propellant rocket motor is shown at the right. In this design, the propellants are brought in through mixers or inlet ports at the upper part of the combustion chamber and are reacted together in the chamber. The resultant gases jet through the nozzle, providing thrust.

It will be noted at once that the liquid-fuel motor, unlike its dry-fuel counterpart, requires the use of separate tanks or containers for the propellants. As a result, the motor considered by itself can be surprisingly small and light. A motor capable of producing 100 lb. of thrust can be held in the palm of the hand. The German V2 rockets made use of a liquid-fuel motor producing 60,000 lb. of thrust (30 tons), and this entire thrust was produced by a motor a little more than 6 ft. long and weighing about 1000 lb.

It should be noted, also, that at the most favorable portion of the V2 flight, this relatively small motor produced power at the rate of well over 600,000

Hp. The liquid-fuel rocket motor may well be, for its size and weight, the most effective device available to man for the conversion of chemical energy into mechanical power. The fuels available for such motors yield several times as much energy, pound for pound, as gunpowder. The Btu content of black powder is about 1000 per lb., and that of smokeless powder, 1870. Gasoline and liquid oxygen, a common liquid-fuel-motor combination, provides some 4220 Btu per lb., more than 4 times that of black powder. And liquid oxygen and hydrogen, a theoretically possible fuel combination, though admittedly a nuisance to handle, will yield 5760 Btu per lb.

Like the dry-fuel motor, the liquid-fuel rocket motor needs no air to push against, and no air to supply either of the components of its combustion. It is, accordingly, completely independent of the atmosphere, and is the motor which rocket engineers expect will drive the long-distance military rockets of the future, the possible mail and express rockets, and even the passenger-carrying long-range rockets, if there are to be any.

Air-Stream Engines.

The rocket motors, because of their simplicity and the furious rate at which they liberate energy, are best suited to the propulsion of rockets, that is to say, projectiles. But there can obviously be another class of jet-propulsion devices, usually called the "air-stream" or "air-jet" engines, which are better for the propulsion of aircraft, because they can exert steady power over long periods of time, and draw one of the components of their propellants, the oxidizer, from the atmosphere itself.

Such engines, unlike the true rocket motors, will be dependent upon the air. They will need no air to push against, of course, but they nevertheless must obtain from the atmosphere the oxygen needed to consume their fuel, and likewise must draw on the atmosphere for a large mass of inert material which can be ejected to provide high thrust at relatively low speeds; low speeds, that is, for reaction motors.

Perhaps this latter point needs to be clarified. The thrust of a reaction motor of course is exactly equal to the mass of the jet multiplied by the velocity of ejection. It is obvious therefore that thrust can be increased either by increasing the velocity of ejection, where the mass must be held to some definite limit, or by increasing the mass, where the velocity must be limited. Because the craft itself moves rather slowly, the engine intended to drive an airplane should have a relatively slow jet, and must therefore eject a relatively large mass. This large mass, together with the oxygen needed for combustion, the air-stream engine can get for the taking out of the air through which it flies. Fig. 2 shows schematic diagrams of three principal types of air-stream engines.

The one at the top, Fig. 2 (*B*), which is the best known, is technically referred to as the "thermal-jet" engine, or more familiarly as the "turbojet." Air enters this engine through a collecting collar at the left, is compressed by means of a rotary air compressor into a combustion chamber, where fuel is injected into it and burned. The resulting gases and the large volume of heated unburned air then pass rapidly out through the nozzle at the right. On the way they are forced to pass through the blades of a gas turbine, which extracts some of the power to operate the rotary air compressor. It will be seen that in this type of device, some of the energy of the jet, as a matter of fact about two thirds of it, is used to keep the cycle going, and only the remainder is available to provide thrust.

Nevertheless, this is a very good engine, and was the type used in England to power the Gloster Meteor which recently set a speed record of more than 600 Mph. It is also the type of engine used in this country to power the Bell Airacomets and the fast-flying P-80 Lockheed Shooting Stars. Toward the end of the war, the Germans had at least two jet-driven aircraft, powered by turbojet engines, which were capable of speeds up to about 600 Mph. They were in production on these engines at the rate of more than 1000 per month.

The second type of air-stream engine is that in the middle, Fig. 2 (*B*), which is referred to by the British as an "intermittent-duct" engine, and by American

engineers as a "resojet" or a "pulsojet." It is also sometimes called a "buzz-bomb" engine, because it was this kind of device that drove the German V1 weapons, or buzzbombs.

In this engine, the action must be started either by compressed air or by rapid forward motion, such as the Germans give it with their buzzbomb launching ramps. When the head pressure reaches a suitable level, the spring-controlled flap valves at the forward end of the tube are blown open, and the air enters the combustion chamber, where it is mixed with gasoline and fired. The resulting blast blows the shutters closed. Expansion then forces the gases of combustion and the column of air out the rear, producing a jet. But this leaves an area of low pressure in the chamber, which automatically opens the shutters again. More air comes in, and the cycle repeated.

The rate of the cycle depends upon the resonance and hence, upon the length of the tube. In the German buzzbomb engine, the tube was about 11 ft. long, and the rate of firing about 40 times per sec. It is because of this resonance effect that this device has been called the resojet or pulsojet.

The buzzbomb engine, at the present state of its development at least, isn't much of an engine in so far as efficiency goes. But it is so light and simple, and so cheap to produce, it may nevertheless have many uses both in war and in peace. It was, of course, well suited to driving the German buzzbomb. The power plant of the buzzbomb represented only 8 per cent of the total starting weight of the craft, and permitted a pay load that represented nearly one half the launching weight.

The third air-stream engine is sometimes referred to as the "continuous-duct" engine, though it is now becoming more familiar under the British name "athodyd" and the American appellation "ramjet." Athodyd, incidentally, is a classical-sounding title which has been made from significant letters of the original British descriptive name, the "aero-thermo-dynamic-duct." Ramjet fits the engine better than any of the other names and is finding increasing favor.

When the ramjet is moving forward (toward left in illustration) at the speed of sound or thereabouts, the air rammed into the open forward end expands in the combustion chamber and is there burned with gasoline or other fuel, to produce an accelerated movement toward the rear and out the nozzle.

Like the rocket motors, the ramjet needs no moving parts whatever for its operation, but it has the peculiarity that it will provide relatively little power until it gets going at speeds near that of sound. Consequently, unlike the turbojet, it can hardly serve as a source of primary power for aircraft, though it may well be most useful as a booster engine for high-altitude fast-flying jet-propelled aircraft using turbojets as primary power.

Efficiency of Jet-Propulsion Motors and Engines.

The efficiency of jet-propulsion motors and egines has been the subject of much discussion, and a good deal of the data that have appeared in print have indicated a low efficiency for jet propulsion, as compared with conventional engines, especially those used in driving the familiar types of aircraft.

While there is no quarreling with these figures, they often present a somewhat distorted view, arising from the fact that in a real sense jet propulsion and reciprocating engines are not competitors. There is a basic relation between speed and efficiency in all types of jet-driven craft, whether aircraft or rockets. This relation shows that mechanical efficiency, that is, the efficiency of conversion of the jet into forward motion of the driven craft, depends on speed and reaches its maximum value only when the craft is moving at the speed of the jet.

Now, the jet speeds of thermal-jet engines are of the order of 1500 Mph. and the jet speeds of the best liquid-fuel rocket motors are around 3500 to 4000 Mph. It is therefore not surprising to find that jet-driven planes are large fuel consumers when they move along at only 300 to 400 Mph. At the speeds which their engines perform best, but to which as yet no aircraft has been designed to fly, namely, at speeds from, say, 1000 Mph. and upward, jet-driven

aircraft will be appreciably more efficient than reciprocating engines or any engines that make use of the propeller.

This discloses, incidentally, why jet propulsion is just now so interesting. What jet propulsion offers us is a new "dimension" in velocities, altitudes, and horsepower available for flight through air or space. Jet engines for aircraft begin to be effective only at the point where propeller-driven aircraft must leave off, i.e., at speeds above 450 Mph., at altitudes greater than 6 to 8 miles, and at power output per engine from 3000 Hp. up.

The maximum horsepower that can be produced by jet engines is not yet known, but undoubtedly exceeds the maximum practical horsepower of any reciprocating aircraft engine of today. It has been calculated that jet engines for aircraft use can probably be built with thrusts as high as 15,000 lb. per engine. Since at speeds of the order of 375 Mph., 1 lb. of thrust is equivalent to 1 Hp., this means that single engines can possibly be built which will deliver, under suitable operating conditions, as high as 15,000 Hp. or more. The altitudes that can be reached with the aid of jet engines are, at least theroretically, greater than those reachable with the ordinary reciprocating engines. It seems probable that jet engines of various types ultimately will be able to fly at altitudes of 10 or even 12 miles, because the forward thrust of the engine itself serves to help gather and compress the air required to support combustion of the fuel.

As to jet-engine speeds; here again we do not know the practical limits, but it seems not unlikely that velocities up to 1500 or 2000 Mph. will be possible in so far as the engine is concerned. It will necessitate important changes in the design of aircraft to fly at such speeds, of course, and it is in the design of the aircraft that the lag now exists. Engines which have so far been developed, apparently would be capable of much higher speeds than any present aircraft can fly. Speeds of even 1500 or 2000 Mph. do not by any means represent the maximum that can be reached with the aid of jet-propulsion motors and engines. When we turn to true rocket motors, velocities measured in miles per second are certainly obtainable.

The best liquid-fuel rocket motors at present developed have jet velocities of between 6000 and 7000 Fps. Since it is quite possible to build rockets which will reach the speed of the jet of their own motors, this means that we can think in terms of velocities during some portion of the trajectory of such a rocket which will exceed 1 mile per sec., or 3600 Mph.

Such speeds are practical, of course, for projectiles; whereas they would probably not be practical for aircraft. We can expect that ultimately various types of jet-driven flying and trajectory craft will be developed covering an entire spectrum of flight velocities, ranging from 500 Mph. or so for relatively slow aircraft, up to rockets which will travel 4000 or 5000 Mph. Speeds even greater than this may be reached. Velocities of the order of 22,000 Fps. or more than 14,000 Mph., will have to be attained to shoot a rocket across the Atlantic Ocean. At these enormous velocities, which are theoretically possible, a rocket would traverse the whole distance from London to New York in a little over 14 min. trajectory time. Equipped with wings to increase the distance and to provide control for landing, such rockets may require a little longer for the journey, maybe as much as ¼ hr.

The Flight of Rockets.

In so far as space and weight are concerned, the motor is a very small part of the total liquid-fuel rocket. Fig. 3 shows the schematic design of a sounding rocket, intended for vertical flight, carrying instruments. This prewar design is somewhat out of date now, but will serve nevertheless to show the principal parts of such a rocket, which do not vary appreciably from the long-range trajectory rockets such as the V2, except in size. This rocket was intended to land by parachute, and hence we have a parachute compartment at the forward end, where the warhead was carried in the V2. Just behind this is the pay-load compartment, where instruments would be carried in a sounding rocket, and where the Germans placed the control instruments used in guiding

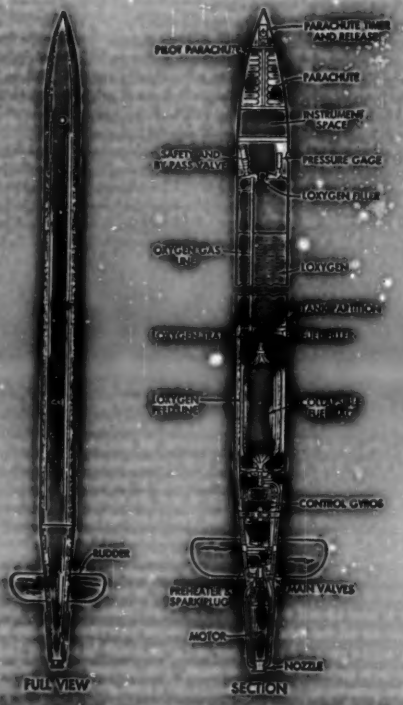


FIG. 3 ONE VERSION OF A SOUNDING ROCKET, WITH GYRO-CONTROL, REGENERATIVE MOTOR AND COLLAPSIBLE FUEL BAG

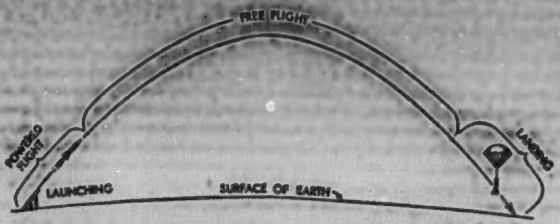


FIG. 4 ROCKET TRAJECTORY, SHOWING THE FOUR PARTS

their V2. What follows, taking in more than two thirds of the length of the rocket, is the space occupied by the propellant tanks. In this space, further dividing walls were constructed to the forward end of the rocket by means of gas pressure, more recently by the pressure of oxygen vapor produced by evaporating some of the liquid oxygen. In the V2 as described, there are four tanks, two large rockets, the main ones, forward of the motor, and two smaller ones [illegible]

In this connection, a rocket which in principle was [illegible] past president of the American Rocket Society, and one of the pioneers in assisted take-off flight, was powered just before the war started. The motor was in the V2, was located at the rear.

This design [illegible] the assembly simplicity of a [illegible] and rocket, and also makes clear [illegible] long-range rocket, which has [illegible] given to me. As a matter of fact, the weight [illegible] ance. For motor thrust, it must be [illegible] the total weight of the rocket at starting operation is to at least two [illegible]

It follows from the [illegible] burned rapidly to [illegible] of the fuel is to be [illegible] at which the fuel can be [illegible] tion of the rocket must be so [illegible] great a velocity too low in the atmosphere, or else heat resistance will rob it of too much power.

Calculation of the rate of combustion therefore is a complicated matter. At the start of the flight, for example, it can be said that the average rate of acceleration for a long-range rocket will be of the order of 3 times gravity. The German V2 started with an acceleration of about 2.5 g, and ended its powered flight with an acceleration of about 5 g.

The trajectory of a typical long-range rocket has four main parts, Fig. 4: First comes the launching, which is relatively brief and may consist, as in the case of the V2, of nothing but a short vertical flight to clear the ground before the aerodynamic control mechanisms were ready to take over.

There is next the highly important period of powered flight, during which the entire fuel supply is burned to give the rocket momentum. In most rockets this is a relatively short period. In the case of the bazooka, it is less than 0.1 sec. In the German V2 it was between 60 and 70 sec, during which time the motor burned about 11 tons of propellants.

By far the longest part of a rocket's flight is the free flight, which begins the moment the fuel is shut off or consumed, and goes until the landing gear, if any, takes over for the final phase of the flight. Returning to our example, the V2 had a free flight of about 4 min., during which time it passed over from Holland to London, a distance of about 200 miles. At the highest part of the flight the V2 was about 60 miles above ground.

In order to permit the rocket to travel such a distance in free flight, the V2 motor had to give it a velocity at the end of powered flight of nearly 6000 f.p.s. (about 3500 mph), and the control gyros had to so manage the flight that the angle of the rocket's motion relative to the earth at the end of powered flight was almost exactly 45 deg.

Conclusion

Though more than 700 years have elapsed since the invention of the first jet-powered projectile by the Chinese, the field of rockets and jet propulsion is still so new that in almost every direction the engineer encounters unknown factors. In matters of temperature, power, velocity, and control, jet engineers are working on the frontiers of knowledge and experience; yet much progress is being made, and the next few years will undoubtedly see spectacular development.

A LIQUID-PROPELLANT ROCKET MOTOR.*

By Lovell Lawrence, Jr.

PRESIDENT, REACTION MOTORS, INC., POMPTON PLAINS, N. J.

The regenerative liquid-propellant rocket motor is the type that powered the German V2 robot bomb at the close of the recent war. This type rocket motor develops forward thrust by the rearward expulsion of combustion products at supersonic velocity. The rocket motor, as distinguished from current aircraft power plants of the jet-propulsion or propeller type, does not operate on atmospheric oxygen, but depends upon a supply carried with the motor. The oxygen is furnished by an oxygen-yielding compound, known as the oxidizer; the fuel may be any hydrocarbon, both of these being known as the propellants.

The jet-reaction engine under consideration utilizes liquids for propellants which are fed into the combustion chamber, and for this reason its operation cannot be compared to the powder or solid-propellant rocket motor whose entire charge of fuel is lodged in the combustion chamber. The liquid-propellant motor has been widely developed in both the United States and Germany because it can be repeatedly operated for long periods of time by merely replenishing the propellant supply.

Construction of Motor.

Basically, this rocket motor, Fig. 1, consists of an injector, the counterpart of the reciprocating-engine carburetor, a combustion chamber, nozzle, and cooling jacket. The injector indicated at 1 is made up of two chambers, one to feed the oxidizer into the injector jet, the other to feed the fuel. An igniter or starter, not shown here, is usually incorporated in the injector when the propellants used are not spontaneously combustible. The combustion chamber and exit nozzle are usually considered as a unit, as shown at 2, since the entire combination must be cooled with one of the propellants flowing in the space formed by the outer jacket and baffle, 3. It should be noted that since this cooling arrangement returns the dissipated heat energy to the combustion chamber with the propellant, there are practically no cooling heat-rejection losses, thus affording a regenerative power plant.

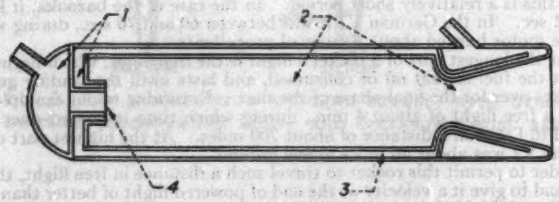


FIG. 1 BASIC SCHEME OF ROCKET MOTOR

After the propellant has traveled up the cooling jacket, it then enters the space at the entrance to the injector jet, and finally enters the combustion chamber, impinging on the other propellant which has entered at 4. It is possible to use as a coolant either the oxidizer or the fuel, depending upon their characteristics.

In the combustion chamber the fuel and oxidizer are burned, thereby converting thermal energy into high-pressure gases which are ejected from the exit nozzle. The exit nozzle changes the internal energy of the rapidly expanding combustion gases into kinetic thrust energy by accelerating the gases to supersonic velocities as they move from the high-pressure region in the combustion chamber to the relatively low-pressure region outside of the nozzle.

* Reproduced from "Mechanical Engineering"—July 1946.

Critical factors in nozzle design are the throat area and exit flare, the throat area being the major factor since it controls the rate of ejection of the gases. The exit flare angle is designed to follow the natural expansion of the gases as they pass from the nozzle throat to the atmosphere.

Theory of Reaction Propulsion.

Now that we have covered the general description of the liquid-propellant rocket motor, let us consider the nature of reaction propulsion, as well as its efficiency. The propulsive action of the rocket motor is described by the fundamental impulse-momentum equation, $F = \frac{mV}{t}$, solved for the resultant force in terms of the change of momentum of the propellants relative to the motor. The thrust force F, is measured in pounds; the propellant mass m, in slugs; the velocity of exhaust gases V, in feet per second; and the time interval t, in seconds. For example, a total mass of propellant consumed at the rate of 8 lb. per sec. and producing an effective jet velocity of 6600 Fps. will deliver a thrust of 1640 lb.

In considering the economy of operation of the liquid-propellant rocket motor, it is advisable to keep in mind the distinguishing characteristics of the motor as previously outlined. Whereas fuel consumption is the yardstick of economy of the air-stream and internal-combustion engines, propellant consumption is the basic measure used for the rocket motor. This factor, naturally, affects the calculation of specific consumption. Instead of computing pounds of thrust per pound of fuel per hour, we must compute pounds of thrust per pound of propellant per hour.

The efficiency problems of the rocket motor are the same as the conventional propeller-type power plant where the product of the thermal efficiency and propulsive efficiency is equal to the over-all efficiency. The thermal efficiency of both power plants is a function of the available energy for propulsion after the engine has converted the thermal energy of the fuel into output shaft horsepower or exhaust-jet energy as the case may be. The propulsive efficiency is a measure of the ability of the propeller or exhaust jet to convert available shaft or combustion energy (respectively) into propulsive effort.

In practice, the termal efficiency may be determined by substituting measured thrust and propellant flow rate in the fundamental impulse-momentum equation $F = \frac{mV}{t}$ and calculating the effective jet velocity. Then the square of the ratio of effective jet velocity to theoretical jet velocity is the thermal efficiency. The theoretical jet velocity is based upon the available Btu content per pound of propellant mixture. The mixture used in this instance is ethyl alcohol (75 per cent) and liquid oxygen. It is important to note, referring back to our example, that at the present time we are able to turn but 28 per cent of the available Btu content into effective energy because of the molecular dissociation and cooling problem at high combustion-chamber temperatures. The thermal efficiency does not change with the velocity of the rocket but does improve with increasing altitude because of reduced atmospheric back pressure.

The propulsive efficiency is a function of the thrust, the velocity of the rocket relative to the ground, the net thermal energy, and the kinetic energy of the propellants by virtue of their motion relative to the ground. Fig. 2 shows a graph of the propulsive efficiency versus the ground speed of a rocket for a jet velocity of 6600 Fps. (4500 Mph.). It will be noted that as the ground speed approaches the velocity of the jet, a maximum efficiency of 100 per cent is obtained.

Fig. 3 shows a comparison of the over-all efficiency versus speed for a conventional engine with propeller, as compared with a liquid-propellant rocket motor. The efficiency scale is the same for both. The velocity scale of the rocket motor is 10 times that of the reciprocating engine. Surprisingly

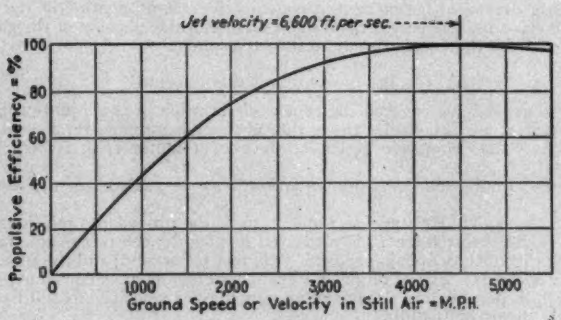


FIG. 2 PROPULSIVE EFFICIENCY VERSUS SPEED

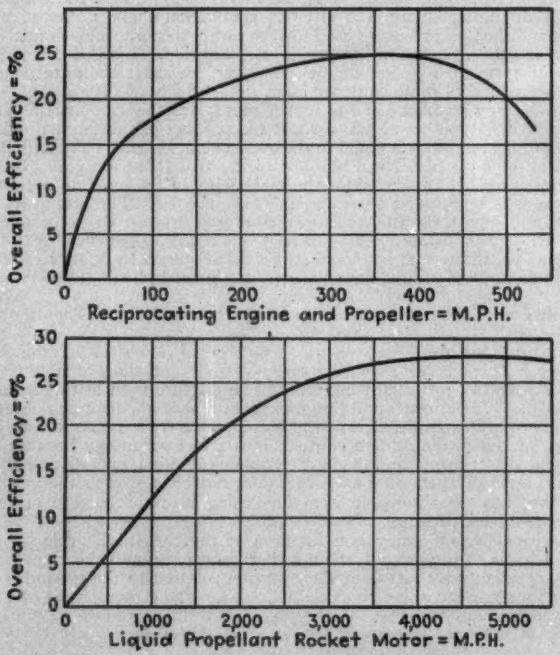
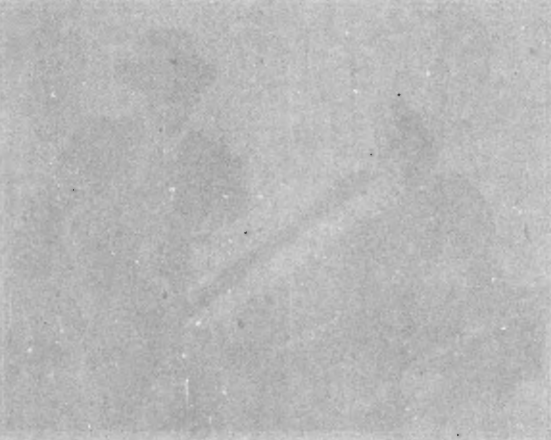


FIG. 3 COMPARISON OF OVER-ALL EFFICIENCY VERSUS SPEED FOR RECIPROCATING ENGINE WITH LIQUID-PROPELLANT ROCKET MOTOR

FIGURE 4—LIQUID-PROPELLANT ROCKET MOTOR ON TEST STAND.

FIGURE 5—EXHAUST FLAME FROM ROCKET MOTOR.



enough, the rocket motor has a better over-all efficiency than the best efficiency of the conventional type when it is operating in the proper speed range near its exhaust-jet velocity. This is possible because 100 per cent propulsive efficiency is attainable for the rocket where the airplane propeller utilizes about 80 per cent of the available shaft power. Since the rocket motor has a 25 per cent efficiency at 2750 Mph., it can get the same mileage per pound of propellant mixture as the conventional-engine mileage per pound of fuel at 350 Mph. Therefore the rocket can travel the same distance in about 10 per cent of the time.

There are of course many other variables affecting the picture of reaction propulsion but it is desirable to indicate the main potentialities in the light of present misconceptions of the operating efficiency of the rocket motor.

Rocket Motor in Early Developmental Stage.

Since the development of this form of propulsion is only on the threshold of extensive progress, it is reasonable to assume that greater efficiencies than 28 per cent will be obtained in the near future.

Now let us take a look at a 1500-lb. thrust unit performing on a test stand, Fig. 4. This 25-lb. unit compares with a 1000-Hp. aircraft engine. The peculiar "beaded" nature of the exhaust flame, Fig. 5, is caused by the reflection of the burning gases from the relatively motionless surrounding envelope of air. Since the jet stream is traveling at about 6 times the speed of sound in the adjacent air, the air is unable to compress rapidly enough and in effect forms a "solid" cylindrical tube through which the exhaust gases move. Eventually, friction slows the outer layers of the flame column down and air mixes with it causing the conical taper at the end of the flame.

In closing, we might mention an outstanding adaptation of the liquid-propellant reaction motor to conventional aircraft in order to emphasize the fact that rocket power has progressed from the experimental stage to a practical type of power plant that is now at hand.

The application we have in mind is the use of the liquid-propellant rocket for assisting take-offs of heavily loaded aircraft whose motors are not powerful enough to supply the necessary thrust. This characteristic of the rocket motor is especially useful on water-borne planes and those which operate from airports at high altitudes where air density does not permit proper aspiration of the engines, thereby reducing power output.

Many more applications which will have a profound effect on transportation and communication are in the not too far distant future. Very shortly the liquid-propellant rocket motor will emerge as a full-fledged aircraft power plant. The age of rocket power is here.

THE MECHANISM OF THE GERMAN ROCKET BOMB ("V2").*

By W. G. A. Perring.

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Royal Aircraft Establishment, Farnborough.

Rockets have attracted the attention of man for a very long time, and the history of rocket development goes back for some 3000 years. Rockets were well known to the ancients, and were used by the Chinese and others. Rockets were also used as a weapon, a piece of artillery, by this country as long ago as the end of the eighteenth century and the beginning of the nineteenth.

In Germany, modern rocket development started seriously round about 1929, and experiments were begun by a group of private individuals interested in the subject. About 1933 the work attracted the attention of the Weapons Department of the German Government, and was virtually taken over by them. In 1937, there was set up at Peenemunde a rocket experimental

* This is a reprint of a paper presented on 12 October 1945 and is reproduced from "The Journal and Proceedings of the Institution of Mechanical Engineers"—June 1946.

establishment, at a cost something of the order of 300,000,000 marks; and the work which was previously carried out in Berlin was transferred there. It was there that the "A4" rocket—the "V2", as we know it—was developed.

The A4 was not the first of the Germans' rocket developments; they worked on other schemes of a preliminary kind. The A1, for example, was quite a small rocket which, as far as was known, was never fired; the A2 was a rocket weighing about 600 lb., which was fired quite successfully and reached a height of about 6000 feet. Work on the A2 rocket began to show the possibilities of further rocket development.

The A4 (or V2) rocket was begun about 1939-40, and the first successful launching was in October 1942. The first A4 rocket the Germans attempted to launch exploded on the ground and blew up the experimental unit concerned; the second went up a few feet and did the same; the third rose some 15,000 feet, and exploded in the air; but the fourth flew about 170 km. and demonstrated the possibilities of long-range rockets. The German authorities, on the strength of this successful shot, started at the end of 1942 the production of the A4—the V2—as a serious weapon.

Fig. 1 gives a general view of the V2 rocket; it is roughly 14 metres long (about 46 feet). The diameter of the body is about 5 ft. 6 in., and the diameter over the stabilizing fins at the rear end is 11 ft. 8 in. It has an initial weight, at launch, of 12.5 tons, of which more than two-thirds is fuel, and it carries a warhead of nearly a ton.

Fig. 2 shows how the interior of the rocket is sub-divided. At the front end is a conical-shaped warhead, and immediately behind the warhead is a compartment containing the main control instruments and the radio equipment. Next come, in the center portion, the two large fuel tanks, then a motor compartment, and finally the combustion chamber and Venturi tube.

The warhead occupies roughly the first 5 ft. 11 in. of the weapon. It is conical in shape, made of mild steel about ¼ inch thick, and is filled with Amatol. The total weight of the warhead and its case is roughly 2150 lb.

Immediately behind the warhead is a compartment sub-divided by partitioning into four quadrants (Fig. 3), housing the automatic pilot and control gear. It will be noticed that the outside skin of the rocket in the vicinity of the instrument compartment is formed in such a way that the instruments can be readily serviced; and since they had to be serviced almost up to the last minute, accessibility was important.

Behind the instrument bay are the fuel tanks (Fig. 4). There are two tanks, each of about 150 cu. ft. capacity; the one at the front end contains alcohol, to which a certain amount of water was added, and the second tank, at the rear, contains the liquid oxygen. This compartment forms the main central compartment and is about 20 feet in length.

Towards the rear of the rocket are the pumps which provided the means of driving the fuel into the combustion chamber, and finally there is the combustion chamber itself and the exit Venturi. Fig. 5 gives a general view of these components.

Around the Venturi are the stabilizing fins (Fig. 6). The four pad pieces carry the internal controllers, which were used for stabilizing the rocket in its flight and for controlling it during flight. In addition there are four small external controllers, one on each of the stabilizing fins.

In general, most of the structure of the rocket was built rather on the lines of aircraft construction, with stringers and formers which can be seen in Fig. 7. The skin itself was of mild steel, about 0.025 inch thick, and the strength throughout the rocket was proportioned by spacing and varying the thickness of the stringers supporting the skin. The main thrust of the rocket, which of course was developed in the combustion chamber, was taken back to the structure through a very heavy steel tubular framework which surrounded the motor compartment, and which also provided the general supporting structure for the turbine and pumps. At the end of the motor bay, at the ends of the fuel tanks, and at the end of the instrument compartment, very heavy angle-frames were provided, which served as transport joints and allowed the rocket

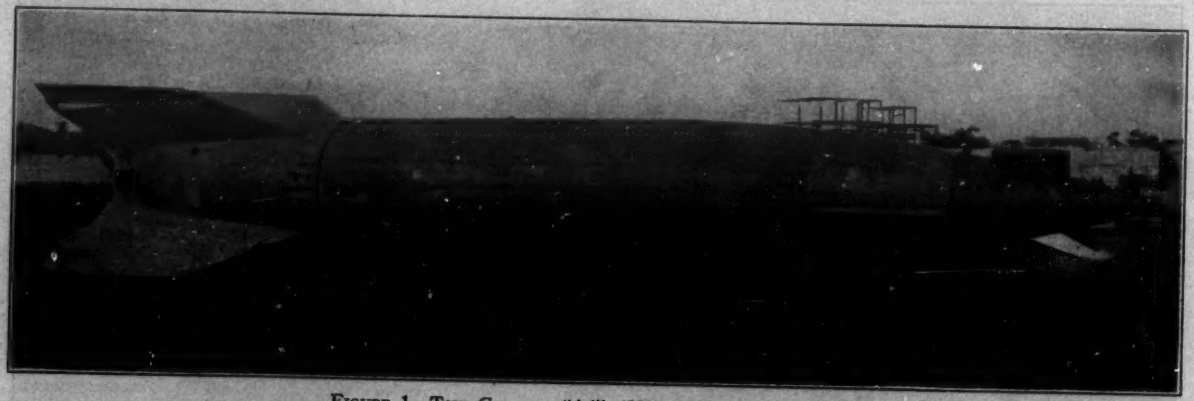


FIGURE 1—THE GERMAN "A4" (V2) LONG-RANGE ROCKET.

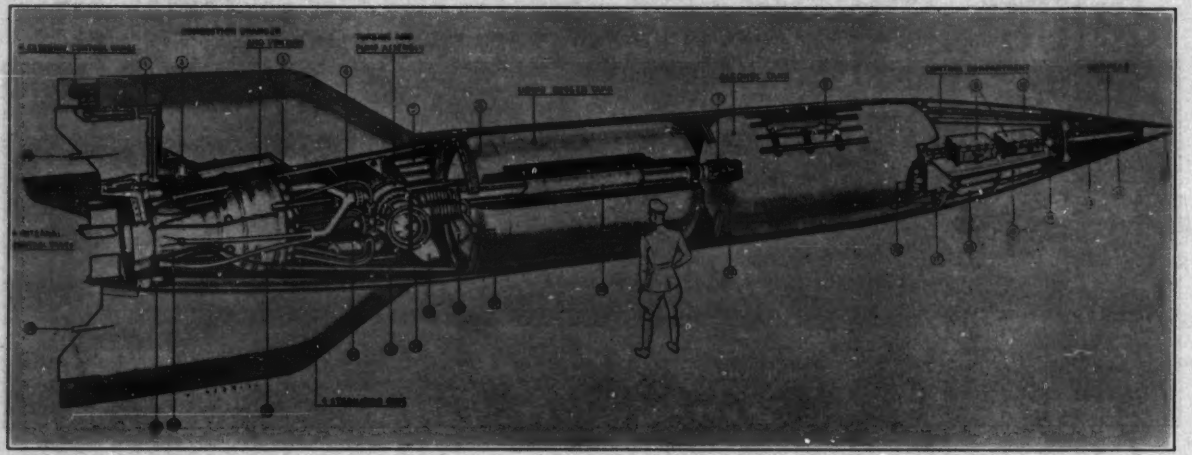


FIGURE 2—ARRANGEMENT OF INTERIOR OF ROCKET.

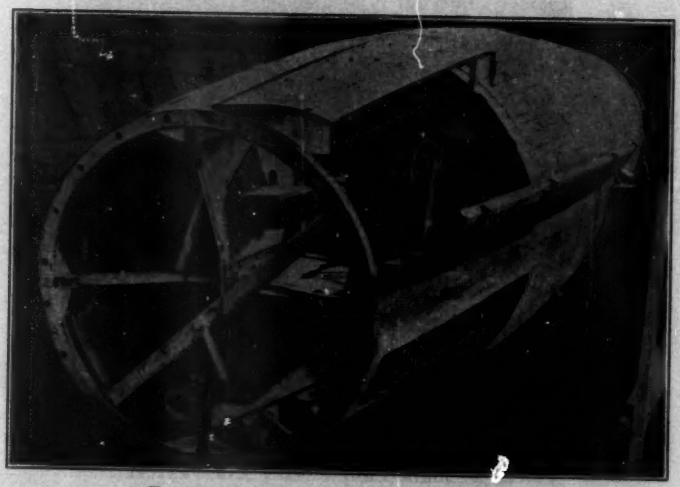


FIGURE 3—RADIO AND INSTRUMENT BAY.

FIGURE 4—OXYGEN FUEL TANK.

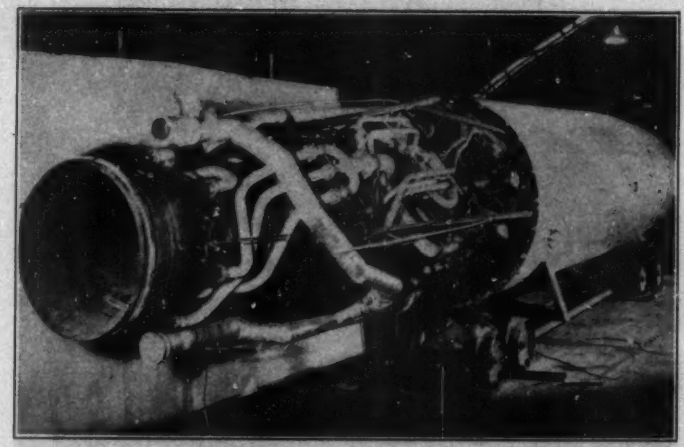


FIGURE 5—MOTOR COMPARTMENT AND VENTURI.

FIGURE 6—STABILIZING FINS.

FIGURE 7—STRUCTURE IN NEIGHBORHOOD OF FUEL TANKS.

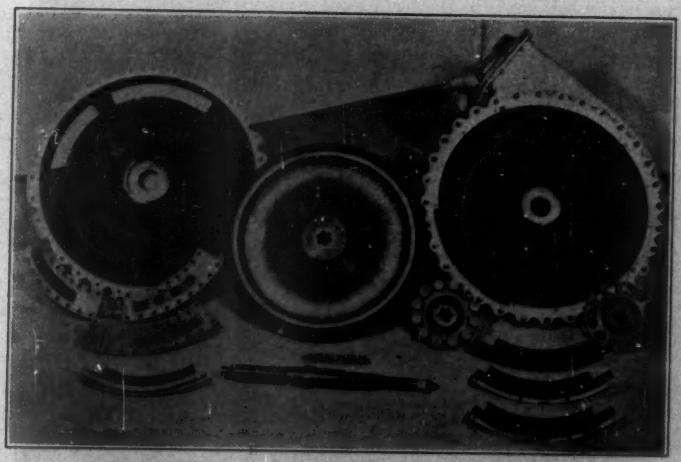


FIGURE 10—TURBINE COMPONENTS (DISMANTLED).

FIGURE 11—TURBINE AND PUMPS.

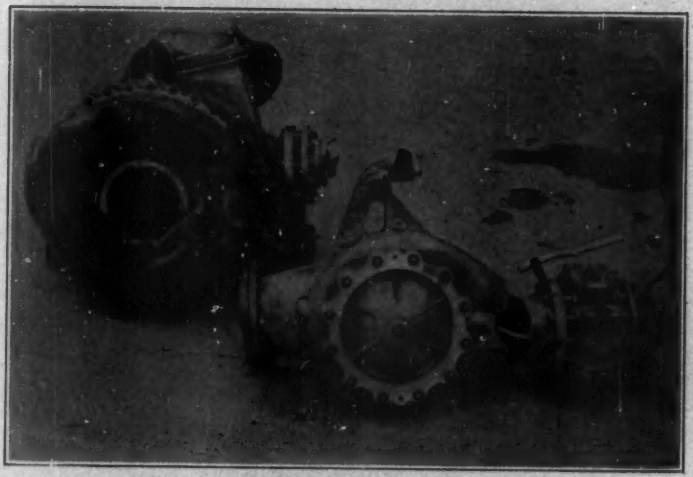


FIGURE 12—FUEL PUMPS.

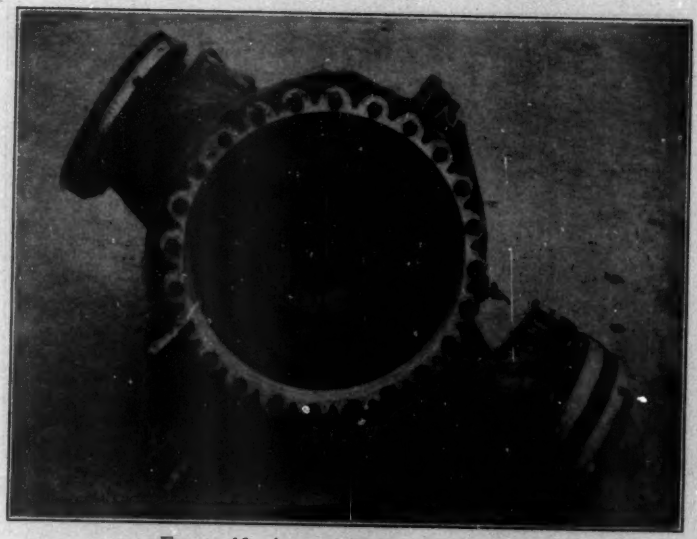


FIGURE 13—ALCOHOL PUMP AND CASING.

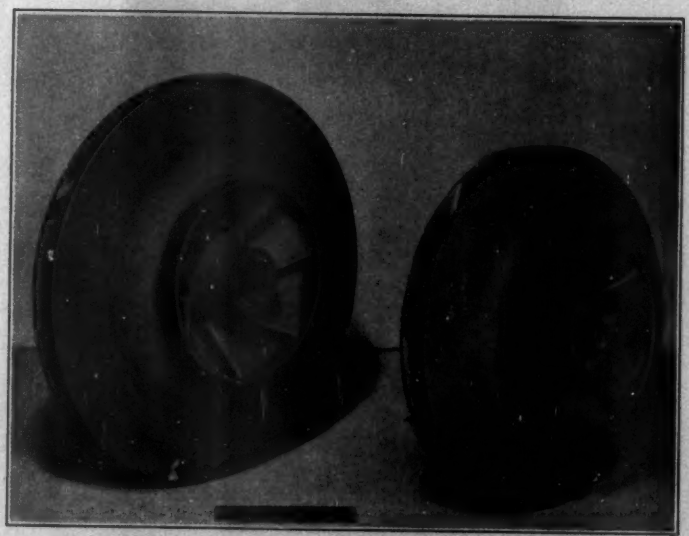


FIGURE 14—PUMP ROTORS.

FIGURE 15—GENERAL VIEW OF VENTURI.

FIGURE 16—BURNER CUPS.

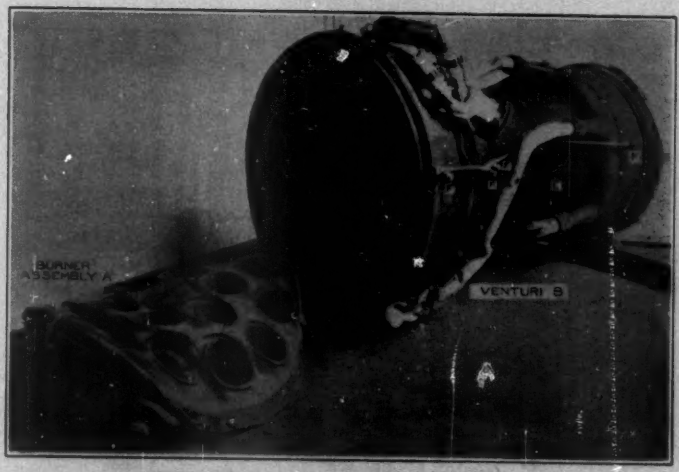
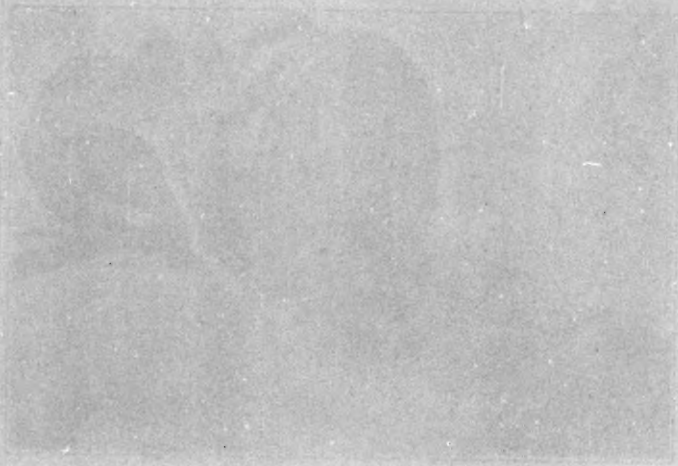
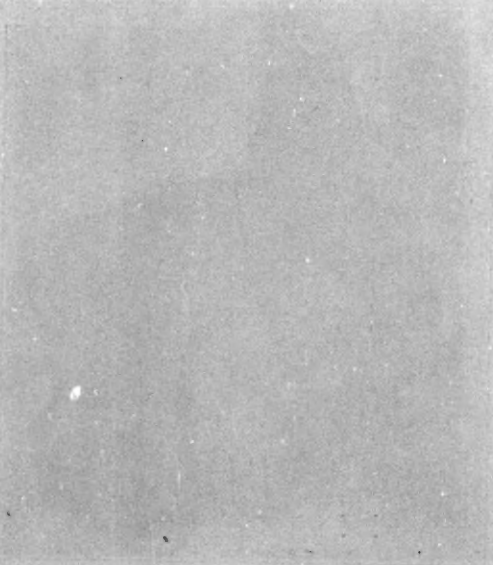


FIGURE 17—ANOTHER VIEW OF VENTURI.

FIGURE 20—GRAPHITE CONTROLLER.





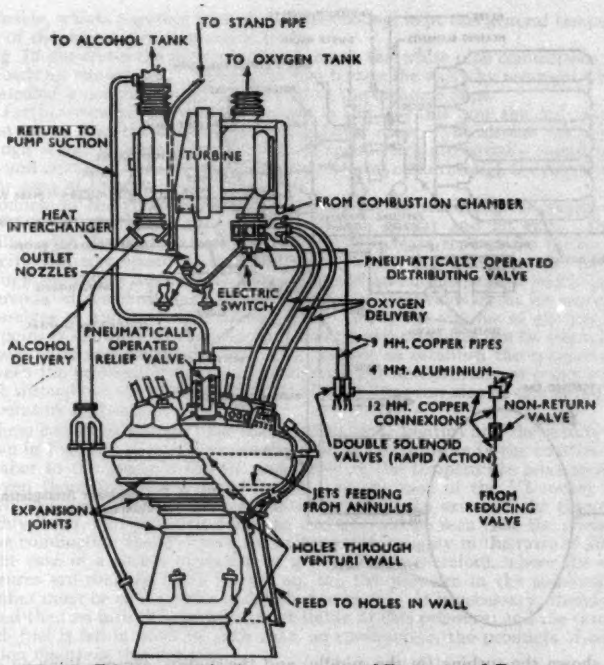


Fig. 8. Diagrammatic Arrangement of Pumps and Burners

to be divided into convenient short lengths for transport and handling during assembly.

Fig. 8 shows diagrammatically the rear end of the rocket with the combustion chamber and Venturi and part of the pumping system. The auxiliary power unit comprises a steam turbine, driving two centrifugal pumps. The pumps draw the fuel from the tanks and convey it to the combustion chamber, through a distributing system. The alcohol acts not only as the fuel but also as a coolant, and is led from the pump to an annulus at the rear of the Venturi; it then feeds back through the Venturi-skin, which is double, to a distribution valve, and then outwards to the mixing cups. The oxygen is fed down by another system of pipes to the eighteen mixing cups, and is then sprayed through a brass rose located centrally in them.

The method of delivering the fuel and driving the pumps is quite interesting (Fig. 9). The generating plant which provides the gases to drive the turbine—and therefore the pumps—comprises a container of hydrogen peroxide, and a container of permanganate. These fuels are driven under pressure supplied by nitrogen bottles, into a mixing chamber, where a mixture, mainly steam, is produced at 420 deg. C. (788 deg. F.) and 350 lb. per sq. in. pressure. The steam is then fed to the turbine—a simple single-wheel arrangment, having partial admission, which develops about 500-600 Hp. at 5000 Rpm.

Fig. 10 shows the actual turbine wheel. The gases are led into the turbine through a distributing ring through the four sets of nozzles shown. In Fig. 11

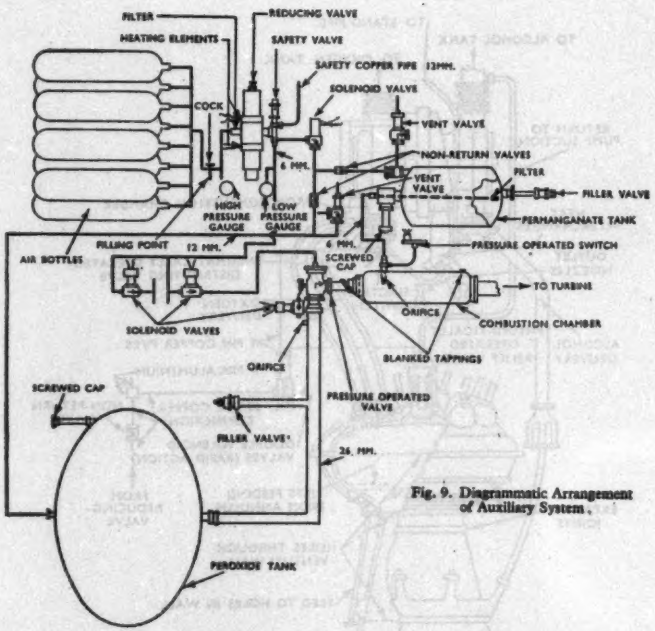


Fig. 9. Diagrammatic Arrangement of Auxiliary System.

are shown the turbine (in the middle) and the pumps, arranged one on each side.

One of the pumps is shown in Fig. 12, with one of the distributors, whilst Fig. 13 is a view of an alcohol pump and its casing. Fig. 14 shows the two pump rotors. It will be noted that the rotors are different in diameter. This is to take account of the difference in density between the alcohol and the liquid oxygen, and is arranged so as to provide that both fuels are fed to the combustion chamber at roughly the same pressure.

Fig. 15 is a general view of the Venturi. It is interesting, because this particular Venturi came to us by accident. It was part of an experimental rocket that got off its true course; it burst in the air, not over this country, though parts of it came into our hands well before any rocket was fired against this country. The experimental rocket had all the features that the later rockets showed, though there were differences of detail. In the Venturi, for example, the end plate which carries the combustion cups, was bolted on to the rest of the Venturi, and was made of light alloy; it was a light alloy casting, whereas in later rockets this end plate was of ordinary mild steel plate and the Venturi was of all-welded construction.

Some of the features regarding the cooling can also be seen. The cooling, as already mentioned, was effected by feeding alcohol to the distributing ring and then back along a cooling jacket to a valve at the center of the combustion face. The cooling provided in this way was augmented by internal cooling. Alcohol was taken from the jacket of the combustion face, fed by small pipes, some of which can be seen in Fig. 15, to a series of radial holds spaced out at points along the Venturi of the rocket. The alcohol led to various points on the inside face of the Venturi, thus providing a film of evaporating alcohol on

the inside, which, together with the jacket-cooling, kept this general temperature of the skin within reasonable limits.

Fig. 16 illustrates the eighteen burner cups; the white pipe connections are the feeds for the oxygen. The center port houses the valve by means of which the alcohol is controlled and distributed to the eighteen cups.

A further view of the Venturi is given in Fig. 17; this time the end plate is taken off, so that the inside of the cups can be seen. The alcohol discharges through about a dozen brass nozzles arranged circumferentially round each cup, and mixes with the oxygen fuel which is sprayed in through the rose fitting in the base of the cup.

Coming to the combustion chamber and the Venturi, Fig. 18 shows the conditions diagrammatically, together with a throat and an exit. Those familiar with thermodynamics will at once appreciate that at the throat the velocity will correspond to the local speed of sound. The gases are passed through the throat at the local speed of sound and are expanded and become supersonic at the exit, where the static pressure conditions in the jet establish themselves as approximately atmospheric. Since the volume of gas passing any point is known, and the velocity, density, and pressures can be related by the adiabatic and Bernoulli laws, it is possible to establish the relationship between the pressure in the combustion chamber and pressure at every other point throughout the system. Similar relationships can also be calculated for temperature and density.

These calculations have been made for an ideal Venturi and the results are shown in Fig. 19. Curve I shows the ratio of the pressure in the combustion chamber to the pressure of exit, and curve II the temperature relationships between those two parts of the rocket. In the case of the V2 rocket the dimensions are such that the area ratio, between the exit and the throat is roughly 3.4/1, and therefore from the curve it will be seen that the pressure in the combustion chamber and the exit must be roughly in the ratio of 20/1. In the case of a rocket operating at ground level, therefore, where the exit pressures are roughly 14-15 lb. per sq. in., the pressure in the combustion chamber must be of the order of 300 lb. per sq. in. It is necessary, therefore, to feed the fuel into the combustion chamber at this pressure; and the rate at which fuel is fed in must be such that, on combustion, the products of combustion maintain this pressure.

The fuel pumps not only have to provide the 300 lb. per sq. in. pressure corresponding to the pressure of the combustion chamber, but also the pressure losses through the nozzles and the pipe system leading from the pumps. The pumps do in fact provide a sufficient fuel flow at about 350 lb. per sq. in. pressure, the amount of fuel to maintain correct conditions in the combustion chamber corresponding to a fuel delivery rate of 275 lb. per sec.

The high fuel rate introduces some interesting problems. At this rate of consumption, the fuel in the two main tanks is exhausted in a little over 1 minute; but since it is very desirable that the tanks should not collapse, provision has to be made to maintain the tanks under pressure during the combustion stage. In the case of the alcohol tank this is done by leading a pipe forward through the warhead to a point near the nose, and making use of the "ram" effects resulting from the high forward speed, which are produced at the entrance to this pipe. The ram effect "pressurizes" the alcohol tank, and provides a head which assists the pumps, and at the same time prevents the tank from collapsing. The ram pressure, however, falls off as the rocket ascends into the very rare atmosphere, and so at some height the pipe is closed, and the tank is pressurized by nitrogen supplied from three high-pressure bottles housed in the instrument bay.

The oxygen tank is treated rather differently. Because of the risk of explosion, it was considered undesirable to introduce foreign matter into the oxygen tank. The pressurizing of the oxygen tank, therefore, was achieved by fitting a relief valve and allowing the rate of evaporation to build up a pressure in the tank. During the burning stage, however, this rate of evaporation was not enough, and it was increased by passing some of the liquid oxygen through a heat exchanger located in the exhaust of the turbine, oxygen from the heat

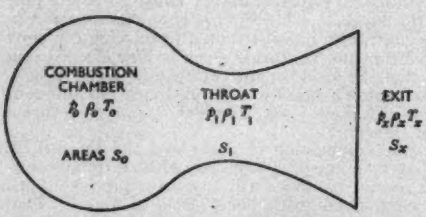


Fig. 18. Approximate Conditions in Venturi

	Combustion chamber	Throat	Exit
Diameter, feet . . .	3·11	1·32	2·41
Pressure, lb. per sq. in. abs.	294	157	14·7
Temperature, deg. C. abs. .	3,000	2,670	1,650
Temperature, deg. F. abs (approx.)	5,430	4,840	3,000
Velocity, ft. per sec. . .	0	2,000	7,000

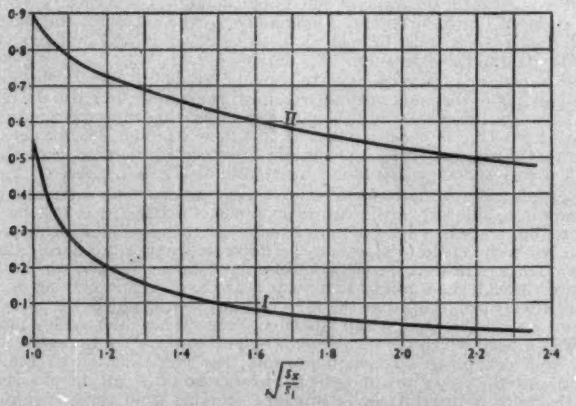


Fig. 19. Performance Characteristics of Venturi

The performance curves relate to a thermodynamically ideal Venturi when $\gamma = 1{\cdot}25$.
The abscissae show the ratio of diameter to throat diameter.

exchanger being fed back again into the oxygen tank to maintain the desired pressure.

Returning now to Fig. 18, the table of figures shows roughly the working conditions of the rocket. The pressure in the combustion chamber corresponding to 15 lb. per sq. in. pressure at exit is 300 lb. per sq. in., and the pressure in the throat is about 150 lb. per sq. in. The temperature of the gases in the combustion chamber is about 3000 deg. C. abs. (about 5430 deg. F.) and this drops to about 1650 deg. C. abs. (about 3000 deg. F.) at the exit. The velocity which, of course, is initially zero in the combustion chamber, rises steadily, and at the throat is 2000 ft. per sec., and at exit reaches about 7000 ft. per sec.

Despite the very high temperatures in the combustion chamber, it was interesting to find that the Germans were able to use mild steel. The worst conditions might be expected near the throat area. A careful examination was made of a number of Venturi tubes, and from this evidence it was found that the skin temperature was never more than about 950 deg. C. (about 1740 deg. F.), nor were any signs of distress found; the cooling, therefore, did its job excellently. The only sign of trouble which was noticed concerned expansion troubles. As more rockets fell into our hands modifications in details were observed, such as the introduction of loops in pipes and connections to avoid these serious differential expansion troubles. In the early rocket special care had always been paid to expansion problems.

The rocket was stabilized by the four very large fins, and it was indicated in passing that controllers were provided to maintain the rocket on its path and keep it steady on that path. Fig. 20 shows one of the four graphite controllers located in the exit jet, on which the high-temperature high-velocity gases of the jet impinge. These controllers provide a very powerful control on the rocket motion.

Fig. 21 gives further details of the controllers. Pairs of internal and external controllers were coupled together to provide stabilization in roll, and maintain direction. These controllers prevented the rocket, once discharged, from rolling around its axis, and at the same time they provided a directional control of azimuth, so that once the rocket was pointed to the target it would maintain direction. The pitch control (or, in aeronautical language the elevator control) is provided by the other pairs of controllers, which are used to steer the rocket from the vertical position in which it is fired, onto a path in which the rocket axis is at approximately 45 deg. to the horizontal, corresponding approximately to the angle for maximum range.

It has always been a little puzzling why the Germans bothered to fit the external controllers. At take-off, the velocity over the external controllers is zero; the control provided by them is therefore zero. As soon as the turbine runs up to speed and the main flow of gases starts, the internal controller becomes very powerful, so the internal controllers in fact provide the main control and the external controllers exert a negligible influence. Near the end of the "all-burnt" stage, when the rocket has reached a height of 22 miles, the density of the air through which the rocket is passing is so low that again the external controller provides almost no force. At no time, in fact, during the motion are the internal controllers inadequate; it is therefore difficult to see why the Germans went to the extra complication of providing both internal and external controllers, seeing that the internal controller can provide all the control that is necessary.

The shape of the trajectory is shown in Fig. 22. The rocket is fired vertically when standing up on its end. After firing, the rocket is turned so that it moves towards the target along a path of the type shown in the figure. At some point about 22 miles above the earth's surface the fuel is either cut off or exhausted, and the rocket then proceeds along a roughly parabolic arc until it descends into the denser air and the path steepens slightly.

Over the first part of its upward course, the rocket acceleration steadily increases as the fuel is burnt, and the rocket weight decreases. Acceleration increases until the "all-burnt" stage; the velocity therefore reaches a maximum at that point and then decreases as the rocket moves up in space. After passing the top of the trajectory the velocity again increases, but as the rocket

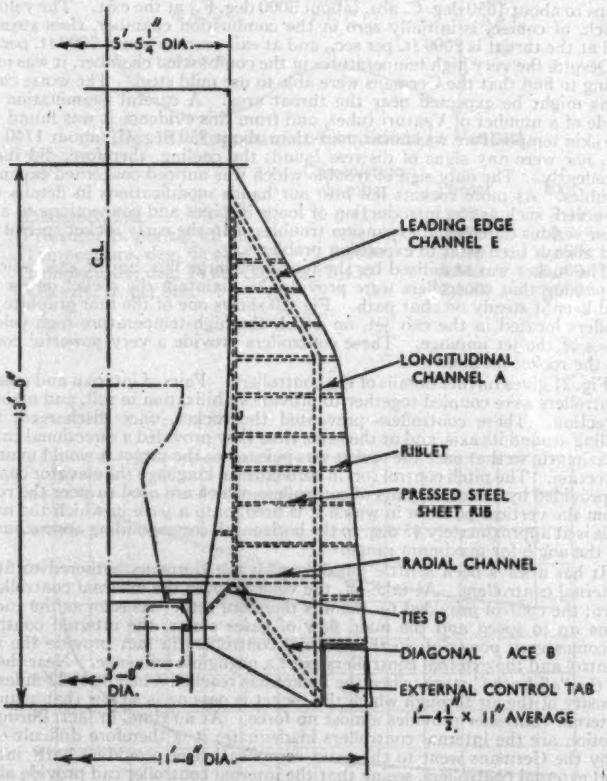


Fig. 21. Diagrammatic Layout of Stabilizing Fin and Controllers

descends into the denser air the velocity again decreases. The maximum velocity at the all-burnt stage is approximately 5000 ft. per sec., i.e., about 3400 Mph. Particulars of the velocity over the trajectory are shown in Fig. 22.

As the rocket leaves the ground, the Venturi is producing about 60,000 lb. of thrust. The weight of the rocket is of the order of 12¼ tons, or 28,000 lb.; the rocket therefore commences to move upwards with a net acceleration of 1*g*, i.e. at the same rate as a body falling freely. As the fuel is exhausted the acceleration increases, and by the time the fuel is nearly exhausted, the weight of the rocket has fallen to about 6000 or 7000 lb., and the thrust has increased slightly, with the result that the acceleration has increased to about 8*g*. In other words, the structure of the rocket is experiencing a force of roughly eight times its own weight. In aeronautical work, this condition would not be regarded as very serious.

Another interesting point is that at the end of the "all-burnt" stage, when the velocity has reached about 5000 ft. per sec., the stagnation temperature is in the region of 1400 deg. C. abs. (about 3040 deg. F.). The skin temperature of the rocket should approach the stagnation temperature and it would therefore become very hot. A careful examination of the skin condition of a number of rockets was made, but no evidence was found to show it ever having reached a temperature of more than about 650 deg. C. (about 1200 deg. F.). The skin temperature therefore is well removed from the stagnation temperature which might have been expected. The explanation probably lies in the fact that conduction plays an important part in keeping the temperature down; but the effect of radiation is perhaps even more important at these high temperatures. The radiation losses vary as the fourth power of the temperature, and these losses exert an important influence in keeping down the skin temperature. Nevertheless, it is obvious from the fact that the skin does reach temperatures of the order of 650 deg. C. i.e. about 1200 deg. F. (perhaps a dull red), that at night it might have been possible to see the rocket.

The existence of this high skin temperature, coupled with the fact that the rocket contains a very considerable liquid oxygen system, emphasizes the importance of taking account of differential expansion. The oxygen tank, for example, which is certainly at a temperature of about −185 deg. C., is next door to a skin which is of the order of 600 deg. C. (about 1110 deg. F.). Changes in length, resulting from these extremes of temperature, are provided for by floating the oxygen tank in guides, which allow an ample end movement; the weight of the fuel being taken through small strut members back to the main stabilizing ring already mentioned, and not carried directly to the skin except at the stabilizing ring.

The German had themselves been concerned about the possible high temperatures which would be reached by the skin, and had carried out a very interesting set of experiments to explore skin conditions. Into the skin of the rocket metal plugs had been inserted which had low melting points, these plugs were coupled through electrical circuits into radio equipment which telemetered the results to ground. As the result of this work the Germans concluded that nowhere on the rocket had the temperature ever reached more than about 600 deg. C. (about 1110 deg. F.), a result that agrees very closely with Allied examination of the surface of the rocket and the state of the paint conditions and the metallurgical conditions of the metal in the skin.

In regard to the actual forces on the rocket near the top of its trajectory, it may be remarked that the pressure of the air on a body is a function of the density of the medium through which it is passing and the square of its velocity. These air forces are conveniently referred to in terms of the indicated air speed, this being the speed at ground level that in the absence of compressibility would give rise to the same pressure reactions as those expressed by the rocket in flight. When near the all-burnt stage the rocket velocity is about 5000 ft. per sec. and near the top of the trajectory this has fallen to something like 3600 ft. per sec. Despite these very high true speeds, the indicated air speed (the equivalent speed at the top of the trajectory) is only about 3½ ft. per sec., so that there is very little force acting on the rocket during the upper half of the trajectory.

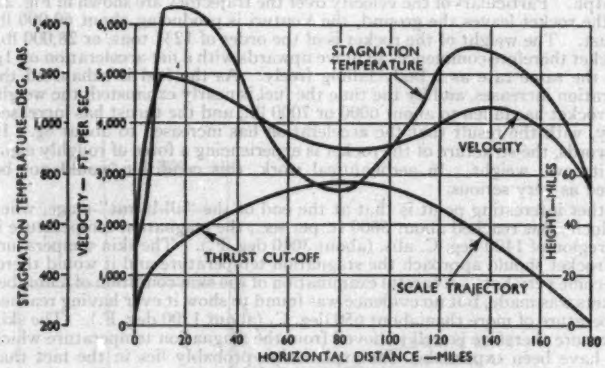


Fig. 22. Typical Trajectory

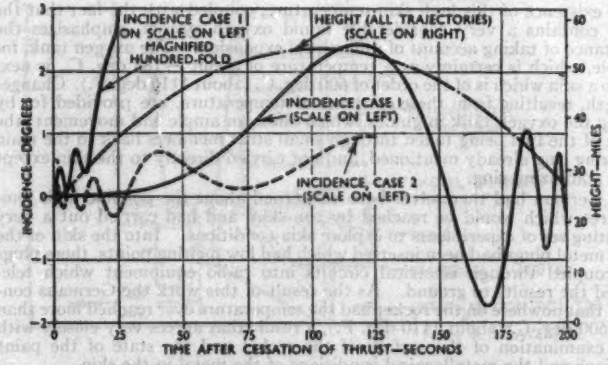

INCIDENCE CASE 1 ON SCALE ON LEFT MAGNIFIED HUNDRED-FOLD
HEIGHT (ALL TRAJECTORIES) (SCALE ON RIGHT)
INCIDENCE, CASE 1 (SCALE ON LEFT)
INCIDENCE, CASE 2 (SCALE ON LEFT)
INCIDENCE—DEGREES
HEIGHT—MILES
TIME AFTER CESSATION OF THRUST—SECONDS

Fig. 23. Rocket Behaviour in Upper Atmosphere

The graphs show incidence and height plotted against time after cessation of thrust.
Case 1: initial rate of pitch and rate of change of path angle equal.
Case 2: initial rate of pitch zero.
Initial conditions: velocity, 4,960 ft. per sec.; height, 120,300 feet (22·78 miles); direction of motion, 0·72 radian (41·3 deg.) to horizontal; horizontal distance from starting point, 9·6 miles; incidence, zero.

This fact led to speculations on the stability of the rocket in the upper atmosphere. If there are no forces acting on it, and the controls are inoperative because the gases have long since been cut off in the jet, how will the rocket behave in upper space?

Accordingly the stability was examined (Fig. 23), and this figure gives some indication of the behavior of the rocket after all-burnt stage. The origin of the curves corresponds to a height of about 22 miles; and the rocket, having reached the all-burnt stage, is travelling as a free body. Two conditions have been considered: (1) when the rocket is just allowed to proceed on its tract without any initial motion to deviate it from its tract; and (2) where the amount of pitch imposed on the rocket is the right amount to turn it on to its correct trajectory. One condition, therefore, favors the rocket continuing on its correct course—at least initially, while the other leaves it to its fate. In both cases the rocket develops an undamped oscillation of increasing amplitude until it goes "over the top". In one of the cases considered the rocket performs one oscillation relative to its main path, the maximum amplitude of which is only about 2½ deg., and in both cases as the rocket descends into the denser air the motion is damped and steadied. Never during its whole flight does the rocket experience a very serious wobble, and its motion is very well behaved, despite the fact that the stabilizing forces are small.

In regard to the distribution of the weight, it was mentioned above that the warhead accounted for 2150 lb.; and naturally the fuel forms a very large proportion of the total weight. It is, in fact, the amount of weight that can be devoted to fuel which really governs the range of the rocket. In the case of the V2 rocket, roughly 19,000 lb., or more than two-thirds of the total weight has been given to fuel. This is a very large proportion, and it is of interest to compare the weight distribution of the rocket with the weight distribution of, say, a high-speed bomber, and with the V1 flying bomb (Table 1).

In Table 1 the first column of figures relates to the bomber, the second to the V1, and the last to the rocket. In the aeroplane, about 29 per cent of the weight is given up to the structure, and it will be observed that the Germans have been very skilful in keeping the structure weight of the V2 down to 13 per cent. The structure weight of the V1, which is more or less an ordinary aeroplane, is 25 per cent. The power plant of a high-speed bomber of the type here considered takes up 24 per cent of the weight, whereas the power plant fitted to the V2 represents only 8 per cent, and that fitted to the V1 also represents 8 per cent. On the other hand, the fuel of the bomber is only 19 per cent of the weight, whereas that of the V2 is 69 per cent—over two-thirds—and that of the V1 19 per cent, practically the same figure as for the bomber. The equipment weight is 13 per cent in the case of the bomber, but very small—2 per cent and 1 per cent respectively—for the V2 and V1. The pay-load represents 16 per cent in the case of the aeroplane; it is extremely low, 8 per cent, in the case of the V2, since so much of the weight has been sacrificed to fuel whereas the V1 has an excellent pay-load.

The next set of figures compare the speed. The take-off speed of the ordinary bomber is 120 Mph., and it requires a long runway. The V2, on the other hand, since it is launced vertically, requires no take-off run, and can be launched from a road or small yard. The V1 requires a high-speed catapult and quite a high launching speed. The maximum speed of the bomber is 400 Mph. and of the V2 3400 Mph. The maximum speed of the V1 is close to that of the bomber, being 350-400 Mph.

A comparison of the fuel consumption figures is interesting. The fuel economy can be expressed as pounds of fuel per horsepower-hour; in the case of the bomber this is 0.75 and in the case of the V1 it is 4.3; in other words, the bomber engine uses fuel six times more economically than the V1 engine. It is interesting to note, however, that near the all-burnt, which of course is a condition favoring the rocket, the rocket fuel consumption does not compare badly with that of a conventional bomber engine, being only roughly twice as great.

A striking figure emerging from this comparison—not included in Table 1 but worth mentioning—is the horsepower that the rocket develops when near

TABLE 1. COMPARATIVE DATA OF HIGH-SPEED BOMBER, FLYING BOMB (V1), AND ROCKET BOMB (V2)

Item	Fast bomber	V1	V2
Percentage weights			
Structure	29	25	13
Power plant	24	8	8
Fuel	19	19	69
Equipment	13	1	2
Pay load	16	46	8
Speeds, miles per hour			
Take-off	120	200	0
Maximum	400	350–400	3,400
Other data			
Ceiling (feet)	40,000	9,000	350,000
Range (miles)	1,600	175	220
Endurance	6·5 hours	30 minutes	5·0 minutes
Fuel consumption (lb. per sec.).	0·57	0·66	275
Fuel consumption (lb. per h.p.-hr.).	0·75	4·3	1·6 (when near "all-burnt" stage)

the all-burnt stage. At that altitude the thrust, which was 60,000 lb. at ground level, has increased, due to the fall of the outside pressure, to very nearly 70,000 lb.; and, since the rocket speed is 5000 ft. per sec., the horse-power being developed is approaching three-quarters of a million—a truly amazing generation of power in such a small unit.

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DISCUSSION.

A digest of the discussion which ensued after the presentation of this paper follows.

In reply to a question as to how the V2 rocket was launched, and how it was directed at a target, it was stated that the rocket was placed vertically and (so far as was known) the main fuel valves were opened, to allow the main fuels to flow to the combustion chamber under gravity. The fuel was ignited by a black powder igniter; and an observer standing at a discreet distance away satisfied himself that the fuel was well alight. It was thought that the fuel lighted quite easily, and burnt without any disturbance. When the observer was satisfied that the fuel was alight, he completed an electric contact, which "pressurized" the hydrogen peroxide and permanganate tanks; the

valve to the turbine then opened, and the turbine was run up to speed. The whole process, from starting of the operation to the attainment of full speed by the turbine, took about 7 seconds. As the turbine reached full speed, the thrust steadily built up, and soon exceeded the weight. The rocket then ascended gracefully, any tendence to wobble being prevented by the automatic pilot, which provided a very powerful control, stabilized the rocket, and maintained it on its right path. The controllers governed the roll, prevented rotation about the rocket axis, and also governed the direction, so that if the rocket was launched with its controllers correctly adjusted is should remain on the right path. The pitch control ensured that it turned at the proper rate.

It was asked why, if the weight of the fuel was so important, the Germans used alcohol, which had a low calorific value. In the reply, reference was made to a technical term used in rocket work—the "specific impulse" of a fuel, i.e. the thrust developed for every pound of fuel burnt per second. For most fuels the specific impulses under practical working conditions were not very different. In the V2 rocket, using alcohol and liquid oxygen, the specific impulse was about 220 lb. of thrust per pound of fuel. Higher specific impulses would be possible if higher working temperatures could have been tolerated. The Germans had in fact to use a dilute fuel to keep the temperatures down. It was difficult to get more out of the fuel, because, unfortunately, when any attempt was made to increase the specific thrust of a given fuel, the pressure rose as the fifth power of the temperature. The temperature and pressure were already perhaps as high as could be tolerated; and 220 lb. per lb. of fuel was therefore a reasonable working value of the specific thrust. It was possible to do slightly better with petrol without incurring some of the difficulties mentioned, but the Germans were probably short of petrol. It would be possible to do still better by using hydrogen, since the other factor affecting the specific impulse was the molecular weight of the gases produced. Specific impulse depended on working temperature on the one hand (which usually could not be increased because of the question of materials), and low molecular weight on the other. The fuel which the Germans used gave them a reasonably low molecular weight, and was, therefore, not a bad choice.

It was stated in reply to an inquiry as to what sort of bearings were used in the liquid oxygen pump, that plain bearings, with plenty of clearance, were employed.

Information was requested on the lagging of the liquid oxygen tanks. Further, it seemed that if the tanks were made to withstand pressure and proper arrangements were made for the vaporization of the liquid oxygen, the fuel could have been fed to the burners without the use of a turbine or pumps at all, simply by evaporation of the oxygen.

The Germans, it was stated in reply, provided glass wool lagging to reduce evaporational losses. The filling of the tanks was one of the last items in the firing procedure. The rocket was made to stand on end in the empty condition and filled while in that position. The fuel was pumped into the rocket from mobile vans. Evaporation losses were small, about 4 or 5 lb. of oxygen per minute during every minute the rocket was waiting to be fired; and the Germans attempted to reduce this waiting time as much as possible. As mentioned earlier, it was necessary, in order to provide sufficient oxygen to feed the fuel forward, to use a heat exchanger. The rate of exhausting the tanks —150 cu. ft. per min.—was quite high. The more important reason, however, why pumps were used instead of relying on pressurizing the fuel tanks, is one of weight. The Germans were able to use a very light alloy tank, which they pressurized to about 1½ atmos., had they pressurized the tanks to 20 atmos. which would have been the pressure necessary to feed the fuel forward at the proper rate, the tanks would have weighed far too much, and this would have increased greatly the structure weight, and reduced the range.

It was asked whether it had been possible to check the resistance of air at the very high velocity of 5000 ft. per sec.? The reply was in the negative, but it was pointed out that since, at the heights at which such velocities were reached, the density of the air was nearly zero, the resistance was not very

large, and had little effect on the rocket motion. Estimates which had been made agreed reasonably well with the ranges that were achieved.

On the loss of resistance at or near the velocity of sound only very limited information was available, because very few results except those on bullets and shells could be consulted. There was a good deal of evidence supporting the view that at speeds above about 1.5 times the speed of sound the theoretical laws were fairly closely obeyed, and at these speeds it was possible to calculate the drag. The drag coefficient rose very steeply at speeds above 0.7 of the speed of sound, reached a maximum a little beyond it, and then fell fairly rapidly; there was a little uncertainty in the region between 0.9 and 1.1 of the speed of sound.

It was asked why the V2 rockets gave rise to two distinct explosions, in some cases the warhead landing some distance from the body and the explosion taking place in the air. In answer, members were told that a number of the rockets which reached this country, and of those fired during the experimental stage in Germany, burst in the air. The exact cause had never been explained, though a number of reasons could be advanced. For example, the method which the Germans adopted for pressurizing the alcohol tank seemed to invite trouble. To have the alcohol tank pressurized by "ram" effect was likely to introduce ram conditions into that tank, with the ensuing high temperatures associated with the adiabatic compression of air at the entrance to the tube. Temperatures approaching 1000 deg. C. (about 1830 deg. F.) or higher might be reached at the mouth of this tube; and if air at that temperature was introduced into an alcohol tank, the risk of an explosion was quite high. It was usually the alcohol tank which exploded and blew off the warhead. The rear end of the rocket usually landed in one piece, and the warhead went on and detonated on impact with the ground.

Reference was made to the fuse mechanism, and it was asked whether there was any truth in the rumor that the fuse worked on a special capacity-inductance system which detonated the charge before the rocket reached the ground, to prevent it burying itself too far in the earth. It was stated that there was a small extension, perhaps about 1 foot long, projecting from the front end of the rocket, and it detonated the charge on impact.

It was contended that in many cases the warhead exploded in the air, and made a puff of smoke, like that of an enormous shell.

In reply, the opinion was expressed that not many warheads exploded in the air, although the rockets certainly did. With regard to the two explosions, and the hearing of two reports, it would be appreciated that the rocket set up a powerful shell wave, making an angle to the nose of the rocket. This wave travelled downwards at the speed of sound, and, depending where an observer was standing when the rocket exploded, it was possible to hear the shell wave, or the rocket explosion in either order, or both together. That was a partial explanation of why two explosions were reported; a roar, which may be quite a crack, coming from the shell wave at the speed of sound, and the second explosion (i.e. that of the warhead) which would travel from the point of explosion at the same speed.

Information was requested on the quantities and quality or standard strength of the hydrogen peroxide and the permanganate, in answer to which it was stated that the amount of hydrogen peroxide carried was 370 lb., and that substance, together with 27 lb. of calcium permanganate (in aqueous solution), provided about 3 lb. of steam a second at 350 lb. pressure to drive the turbine. The peroxide was about 80 per cent concentration, and at that concentration it appeared to be quite stable.

In reply to an inquiry as to the type of engine used in the V1, it was explained that it comprised an impulse duct—a tube with a grid over the entrance. The grid in turn comprised a large number of valve openings of simple form, and the tube length was such that resonance was set up in it, with a frequency of about 47 a second, each "pulse" of the resonance creating a suction behind the grid plate. Air was drawn into the tube through the grid. The suction was followed by a pressure resulting from the combustion of the fuel which mixed with the incoming air; and so the pulsation was maintained.

Some further information was given on the fuel system. The liquid oxygen tank was of ordinary light alloy, the pump was of steel, and the general piping throughout was again of light alloy. In spite of the very high acceleration, no trouble would be experienced with cavitation in the fuel system once the rocket had started, because the fuel system itself would be subject to an acceleration of 2*g* at starting, rising to 8*g* near the end of the "all-burnt" stage; the acceleration assisted the fuel feed to the pump. Provided that priming was properly carried out (and this was checked by observing the combustion), there was no likelihood of cavitation.

In regard to the height reached by a V2 rocket, in comparison with the height to which it would be necessary to fire a rocket to overcome the gravitation of the earth, the answer was given that it was a simple matter to determine the height reached by a V2 rocket; since its path was practically parabolic, its height must be roughly one-quarter of its range. The determination of the other height was not so easy, because height did not matter so much as speed. If one could travel at about 24,000 Mph., it would be possible to steer oneself to any height, and to overcome the earth's gravitation. That was not outside the realms of possibility. Imagine a very big rocket in which the warhead was replaced by a smaller rocket, and the warhead of the small rocket replaced by the V2 rocket described above. Such a three-stage rocket would reach the speed necessary to pass outside the earth's gravitational field.

The maximum efficiency of the V2 rocket could only be assessed in terms of the figures cited in discussing the fuel consumption. At altitude the fuel consumption compared not unfavorably with the ordinary reciprocating engine. The reciprocating engine could not operate at that altitude at all. The rocket had to carry its oxygen with it because there is nothing to burn at such altitudes, but the rocket burnt its fuel very economically when it travels at such a high speed.

In regard to testing, it was considered that the Germans carried out a great deal of check testing before firing—e.g. testing the characteristics of the pumps, etc., but they could not fire the rocket motor to judge its performance. If a rocket failed, due to any reason unknown, it was believed that it was their practice to return it to store and never try it a second time.

If, as was stated, no specially prepared launching sites were needed, it was difficult to see why the Germans built such vast concrete structures on the "rocket coast" of France. In reply, the opinion was given that in setting out to bombard this country the Germans knew they would be inviting trouble, and since numbers of troops were needed, they wanted to provide their crews with reasonable conditions of protection, so the thick concrete structures were built.

The question was raised as to whether the existing rocket was in any way an accurate weapon. For instance, did the Germans definitely aim at certain parts of London?

In reply, the difficulty in answering the question was acknowledged. The Germans began the production of the V2 rocket three or four months after the first successful shot. But in all experimental work, many difficulties must still be faced after the first successful shot. Fragments of rockets collected in this country clearly showed signs of development and evidences of change. The designer of the rocket was fully aware of its shortcomings, but also very optimistic about its possibilities, so that it would be unfair to attempt to answer the question, because the rocket designer would simply state that the rocket was a very undeveloped article, but the best that could be produced in the time. It was certainly possible to control the rocket by wireless means, but details of the actual control could not be released.

The method of launching the rocket was again referred to, and it was asked whether it was first launched vertically upwards and then diverted at an angle of 45 deg., and whether that was the most economical way to get the longest range or the maximum pay-load? Would it have been more economical to adopt a flatter trajectory, so as not to devote so much energy into pushing it into the air, only to come down again? In answer, it was stated that, clearly,

it paid to send the rocket up to regions where the air had little density as quickly as possible. It paid, therefore, to send it up vertically.

Reference was made to the design of the motor attached to the fins—first a shunt motor, and later a compound-wound motor, the first being made of cast iron, which one would not expect on aircraft. No definite reason could be given in reply, but a possible explanation was that several groups of German technicians were working on the control system; it was, in fact, a feature of the rocket that underwent more change than anything else. Different firms might have developed different methods. It was clear that, in regard to the control system, many firms were making contributions.

It was asked whether it was speed or acceleration that affected the possibility of overcoming the earth's gravitational field. The opinion given in reply suggested that ultimately it was a question of speed. It was necessary to reach a definite speed; how that speed was reached depended on how long the acceleration was maintained. The V2 rocket accelerated from 2*g* up to 8*g*. Had it carried more fuel it would, of course, have accelerated up to much higher values than 8*g*, and would have continued to increase in speed. The acceleration affected the time necessary to reach a given speed; but the speed determined whether the rocket could move out of the earth's field. Whether or not it would be possible to find material to withstand the necessary temperatures, associated with such speeds was very doubtful; for these would be enormous, even though they were greatly reduced by radiation.

It was further pointed out that the velocity of the V2 rocket was a mile a second. The speed necessary for a projectile to leave the earth was 7 miles a second. After some interval the velocity of the V2 rocket dropped from 5000 to 3500 ft. per sec., which was of the same order as that of a high-speed shell. These speeds were far from velocities suitable for a projectile to leave the earth —only one-seventh of the figure in fact. Rockets had not nearly attained the speeds necessary for leaving the earth's gravitational field. The power generated by the V2 rocket, was, as already mentioned, some three-quarters of a million horsepower. One must not be appalled at this figure, because the rate of generation of power of a shell in its explosion was much greater; but with the V2 rocket it was a very high rate of generation of power *under control of some sort*. That was the importance of that seemingly high figure.

Reference was made to a statement which had appeared in a technical magazine that the Germans could get an approximate idea of where a rocket landed by means of seismographs, and it was asked whether there was any truth in this. In reply, the opinion was given that the Germans did employ seismographic methods to try to detect the fall of rockets. Whether they obtained any results was not known. It would be difficult to do so without knowing a great deal more about the substratum of the earth than they presumably did; but it was fairly certain that they called in all their experts, and considered the possibilities of such a method.

It was asked whether the V1 flying bomb, as it was so simple, had any future. In answer it was stated that it was a very cheap engine to make, but it was very noisy and subject to great vibration. Except, therefore, for applications where the power unit was intended to be thrown away, it was not considered that it had a future.

Finally, a reason was sought for the difference in the type of explosion produced by the V1 and V2. (The V2 seemed much sharper and more of a detonation, and the V1 usually a thud.) In reply it was stated that the fuse on the V2 rocket was set very lightly; it exploded very close to the surface, and in any case was not intended to penetrate deeply, while the V1 was a definite blast weapon. Moreover, the explosive used in the V2 was less violent and active than that used in the V1. The difference in the audible result was possibly due to the fact that while the V1 flying bomb exploded above the surface, and was a first-rate blast weapon, very often the V2 rocket buried itself and detonated. Apart from that, people very often mistook the crack of the shock wave for the explosion itself.

ROCKETS.*

Spectacular firing of V2 rockets at White Sands, New Mexico, begun on May 10, will be continued at the rate of one a week for a minimum of 25 weeks. Assembled from captured V2 rocket parts by German scientists brought here especially for the purpose, these rockets will help us obtain fundamental information to develop more efficient, longer-range missiles.

Besides the Army Ordnance Department, in charge of the V2 test program, there are associated: The Army Signal Corps, who are interested in the physics of the upper atmosphere and are supplying electronic tracking apparatus; the Army Air Forces, who look upon the V2 rockets as "pilotless aircraft"; and the General Electric Company, which has a crew of technicians and scientists at White Sands to help assemble the V2's to replace missing parts and repair damaged ones, and to design test stands and electronic controls.

The V2 will not be the only rocket fired at White Sands. Prominent in the program will be periodic launching of the "WAC" rockets, American missiles developed by Army Ordnance. These rockets operate on the same general principles as the V2, but are smaller and lighter, and do not have the elaborate controls and range of the German rocket.

White Sands Tests.

The physics of the upper atmosphere is expected to be probed at the White Sands tests. The V2 rockets are expected to reach an unprecedented height of 120 miles before hitting the desert sands about 80 miles north of the firing platform.

The Army Ground Force's new guided missiles unit, the 1st Anti-Aircraft Artillery Guided Missiles battalion, is performing its first mission in firing the V2 rockets. A 9-man panel consisting of representatives of the General Electric Corporation, Princeton University, Harvard, Massachusetts Institute of Technology, University of Michigan, The Army Signal Corps, and the Applied Physics Laboratory at Johns Hopkins University has been organized under the direction of Dr. E. H. Krause of the Naval Research Laboratory to coordinate all scientific data on the physics of the upper atmosphere.

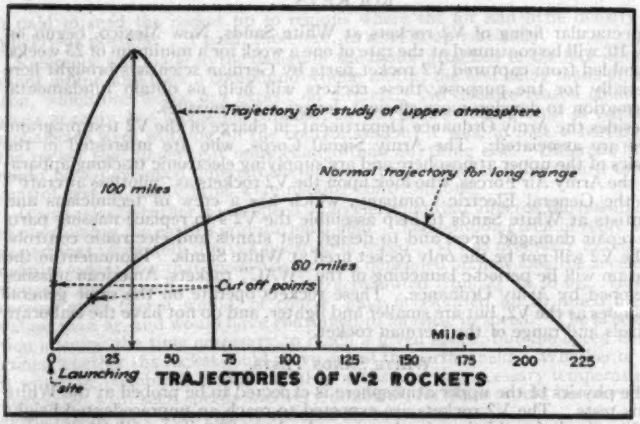
Rocket experts will trace the flight with the aid of two-way radio, radar equipment, complete decontaminating equipment and air pressureizer and long-range telescope.

The rocket will be used to test the VT (proximity) fuze, telemetering equipment that furnishes data on pressures, temperatures, velocities and accelerations; control components that furnish roll and stabilization and fix the range and accuracy of the missiles.

Seventeen checking stations are used in tracking the V2. Four different tracking methods are in use: Radar, optical, photo, and sonic (Doppler). The radar methods involve impulses from a unit in the nose and reflections from three tail surfaces. Both optical and photo tracking are achieved with an ingenious German instrument, the Askino theodolite, set up 8 to 10 miles from the launching site. The unit has a tremendous lens, which enables two operators to watch the V2 for 150 miles visually. A built-in camera records the action at 60 frames per second. Three of these instruments at widely separated points permit checking of "roll" of the projectile by showing the special pattern painted on it.

Newly developed radio beacons, which contain their own power supply and are actually miniature radio receiver-transmitters, have been fitted into the V2, in place of the warhead, for one tracking device. Antennas are in plastic housings on fins. During flight, the receiver is triggered from a ground radar set by pulses that cause the transmitter to repeat the pulses to the radar. This permits the trajectory to be recorded photographically. The Signal Corps radar set used is modified from a unit developed during the war for detecting aircraft and directing antiaircraft guns. Conventional radar equipment also tracks the V2 for its entire flight without the aid of beacons.

* Reproduced in part from "Product Engineering"—July 1946.



Average height expected to be reached by the V-2 this summer is 100 miles, in a special trajectory designed for study of the upper atmosphere. Maximum height hoped for is 120 miles.

Upper Atmosphere Studies.

The lack of elaborate control apparatus in the WAC rockets indicate that they will probably be used as a "sounding" rocket, to probe the upper atmosphere. Both the V2 and the WAC (expected to reach a height of 80 miles) rockets will carry instruments to speed data back to earth.

Radar can track projectiles at supersonic speeds, and sections of a rocket can be detached by radio control to parachute instruments down. These include ozone analyzers and ionization meters that record data about cosmic and ultraviolet radiation. Special glass-lined chambers that open and reseal automatically have been built to bring back samples of the upper atmosphere. Some rockets also carry wide-angle infra-red cameras to photograph the earth from high altitudes.

Of greatest interest to scientists is the ionized atmospheric layer above the stratosphere, the ionosphere, which begins about 58 miles above the earth's surface. The sounding rockets should reveal much about the nature of the ionosphere as a shield protecting the earth from the intense bombardment from outer space. The filtering action of the ionized layers, on external radiation, is believed to be similar to that affecting radio waves from the earth. Cosmic rays, which are believed to have some influence on life by disturbing hereditary factors in living organisms, penetrate certain layers and not others. Other phenomena to be investigated are "magnetic storms", temperatures at various atmospheric levels, radiation from atomic gases and gaseous structure of the atmosphere, to its outermost limits.

The V2 Rocket.

The German V2 rocket represents the first successful attempt to build a large-scale projectile with a liquid propellant rocket motor. No doubt more efficient rockets, using different propellants and including many radical designs, will be built in the future. But the V2 itself is a radical departure from conventional rocket thinking; it is for this reason that it is being studied at White Sands.

The main assemblies of the V2, as used for military purposes, are:

1. Nose with 2000 lb. explosive warhead.
2. Compartment with control equipment.

Elevating boom, designed in Germany, is known as the "Meiller Wagon." It carries the V-2 and sets the rocket in place by means of a motor-driven hydraulic system. The carrier-boom is equipped with platforms which enable workmen to climb up its ladders to make adjustments. Feed lines for fuels are built in.

3. Two large aluminum fuel tanks, one holding about 7500 lb. of alcohol and the other about 11,000 lb. of liquid oxygen.
4. Turbine and pump assembly with a gas generator to drive the turbine.
5. Large combustion chamber and venturi into which the alcohol and liquid oxygen are forced through a series of jets.
6. Two sets of control vanes. One set operates internally in the jet stream and the other externally on the edges of the four stabilizing fins.

The rocket stands in a vertical position on a concrete platform or hard surface. The turbine, driven by gas generated from concentrated hydrogen peroxide mixed with a calcium permanganate solution, powers pumps that force the liquid oxygen and alcohol into the combustion chamber. This mixture is then ignited by remote electrical control, and the rocket takes off.

Once ignited, the mixture of oxygen and alcohol continues to burn violently. Combustion products are forced out at high speed through the orifice in the rear end of the venturi as a jet of very hot gas. The energy so liberated creates a thrust of about 26 tons, which propels the rocket.

V-2's Vital Statistics

Maximum range	230 mi.
Weight, unfueled	10,000 lb.
Weight, fueled	28,380 lb.
Weight of warhead	2,230 lb.
Alcohol	8,304 lb.
Oxygen (liquefied)	10,800 lb.
Overall length	46.05 ft.
Body diameter	5.41 ft.
Width across fins	11.69 ft.
Fuel capacity	2,500 gal.
Maximum velocity	5,600 ft. per sec. 3,800 m. p. h.

The V2 starts by climbing vertically, but a gyroscope control within the projectile automatically moves the control vanes, causing the unit to curve away from the vertical toward the target. The mechanism is so arranged that the rocket points upwards at an angle of 45 deg. about one minute after launching, and at this time the fuel supply is cut off either by remote control from the ground or by automatic instruments in the rocket.

The point at which fuel cuts off determines range. If fuel burns for a long time, high speed and long range result. If it burns for a shorter time, speed is less and range correspondingly decreases. Since the rocket points upward at 45 deg. when fuel cuts off and travels at about 3000 Mph., it continues upward following the path that would be taken by a shell fired at this angle. There is a little air resistance in the upper regions and the rocket eventually reaches a height of over 60 miles above the earth's surface (for a normal trajectory) and comes down still following the parabolic path a shell would take.

The WAC Corporal.

American research in liquid-fuel rockets has resulted in the "WAC" series—WAC Private, WAC Corporal and WAC Sergeant rockets. Developed independently of the German V2 rockets by the Army Ordnance Department and the California Institute of Technology, the WAC Corporal is the outstanding member of the series.

Unlike the V2, the WAC Corporal has no control system except for three stabilizing fins. It is launched vertically from a triangular 100-ft. tower. It is boosted during the first moments of its flight by a solid-fuel step rocket. The latter is reported to be the "Tiny Tim" rocket, but this report has not

been commented on by military authorities. The step rocket brings the WAC to supersonic speed in 0.6 second, then falls away to let the liquid-fuel motor carry on alone.

The Corporal is 1 ft. in diameter, 16 ft. long, and weighs 700 lb. at launching; about half this weight is oxidizer and fuel. Its body is made of steel, aluminum and magnesium.

Although full technical details of the WAC have not been disclosed, it is known that its motor is basically similar to that of the V2, except that the fuel and oxidizer used are different. Aniline is the fuel, and nitric acid is the oxidizer, analagous to the liquid oxygen in the V2. This fuel was chosen because the WAC Corporal was originally intended for use as an antiaircraft rocket; it was felt that liquid oxygen would evaporate and thus would not be suitable for "sudden" firing, requiring advance setting.

An improved model of the WAC Corporal, to be known as the WAC Sergeant, is being built by Army Ordnance.

JET PROPULSION ENGINES AND PROPELLER DRIVE GAS TURBINES—THEIR APPLICATION IN FUTURE AVIATION.*

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Summary.

It is the purpose of this paper to give a brief description of the operating principles and major design features of aircraft gas turbines, and to evaluate the performance characteristics of jet engines and gas turbine propeller drives to determine how these new power plants may be applied in future aviation.

Operation of Jet Engine.

Contrary to the rocket which carries along its own oxygen to burn with the fuel, jet propulsion engines bring in the atmospheric air from the outside (Fig. 1).

Contrary to the "buzz" bomb, the action of the jet engine is continuous rather than intermittent. The principle of the jet engine (or "turbo jet" as it is sometimes called) is very simple and not unlike that of the hot air engine of former decades. It will be recalled that in the hot air engine air is compressed by a piston. The air is expanded by heating it and the expanded air then does work on another piston. Because the specific volume of the air has been increased in the heating process, it can supply more power than what it took to be compressed. This surplus is used to provide useful shaft horsepower.

While in the jet engine the main elements are rotating, and not reciprocating parts, the principle is just the same. Air is pumped in by a compressor. Entering the combustion chamber, the air is heated by burning liquid fuel in it. The expanded hot combustion products are made to drive a turbine, the sole purpose of which is to supply power to keep the compressor and the small accessories going. In the jet engine the useful horsepower appears not in the form of shaft horsepower, but in the form of a high velocity jet, the reaction of which serves to propel the airplane.

Gas Turbine Propeller Drive.

The term "aircraft gas turbine" is applied not only to the "jet" engine, but also to a propeller drive in which the gas turbine replaces the reciprocating engine (Fig. 2). In this form we have again a compressor, a combustion chamber, and a turbine followed by an exhaust nozzle. However, in this form of gas turbine the turbine element takes out more power than is needed to drive the compressor. This surplus power is used to drive the propeller through suitable reduction gearing. A small part of the energy (about 20 per cent.) remains in the jet, where it furnishes useful power.

* Reproduced from the March 1946 issue of "the Journal of the Franklin Institute."

Design Principles.

Jet engines have been built in several forms. One distinguishes centrifugal and axial flow compressors depending on whether the air particles leave the rotating member in a radial or in an axial direction. While the centrifugal compressor contains one or more vaned impellers, the axial compressor rotor contains a large number of blades, which like propeller blades, push the air towards the combustion chamber. Either type has found use in jet engines.

Fig. 3 shows schematically the "Whittle" type engine, as built in 1940 on the basis of the suggestions of Group Captain Whittle, who had made concrete proposals for jet engines in England since 1930. The centrifugal design is the one followed by the best known English builders, among whom Rolls Royce and DeHavilland are outstanding.

In this country, the axial flow type of jet engine (Fig. 3) was pioneered by Westinghouse under sponsorship of the U. S. Navy, Bureau of Aeronautics. Independently, the Germans used axial flow compressor on all their jet engine designs known to us.

Jet propulsion makes possible the use of exceptionally "clean" airplanes capable of high speed. In fact, jet propulsion does not offer advantages in performance unless it is applied to high speed aircraft. The higher the flight speed the more important it is to make the airplane just as streamlined as possible. In terms of the engine, this means that a small frontal area (a small diameter) is extremely desirable. The choice of an axial flow compressor permits a design with a small diameter (the two types shown on Fig. 3 are approximately to scale).

In general, the axial flow compressor seems to have a slight edge in efficiency. On the other hand, there appears no question but that the centrifugal compressor is the less expensive to build, and that for very small sizes its efficiency may prove equal or superior to that of the axial flow compressor.

In the centrifugal type engine the air must be turned around—before and after the compressor—several times before it leaves the exhaust nozzle. In the original Whittle type the air has to make eight right angle turns before it emerges. Each turning operation involves a loss of energy which is avoided in the "straight through" axial flow design.

An axial inlet to the engine is important because it permits the aircraft designer to bring in the air with a minimum of loss. Thus he can take maximum advantage of the so-called ram effect—the increase in engine inlet pressure resulting from the forward speed of the plane. High inlet pressure results in a high power output and high efficiency of the power plant.

Of interest is also the different treatment of the burner design in the two types of engines shown. In the Whittle type engine combustion takes place in a number of cylindrical burners, called "cans" mounted along the outside of the engine. In the axial flow design, shown in Fig. 3, there is only a single combustion chamber of annular shape.

Description of Engines.

By way of example, several axial flow engines are shown in this article.

The first American designed jet engine, now known as the Westinghouse 19A engine (Fig. 4), was a good example of a streamlined design of small frontal area. This engine, which is good from some 1,300 Hp. at 450 miles per hour, has a diameter of only 19 in. It was designed to be flown as an exterior booster engine underneath the Navy "Corsair" fighter.

This engine, which is now obsolete, drives only the accessories necessary for its own operation; there is no provision to drive aircraft accessories such as generators, hydraulic pumps or vacuum pumps.

Fig. 5 shows the 19A engine as it was mounted underneath the "Corsair." It is of interest to note that the ratio of the diameters of the 1300 Hp. jet engine and the 2000 Hp. reciprocating engine driving the propeller is about 1 to 3.

The 19A engine was the first of a family of axial flow jet engines.

Fig. 6 shows its successor, the Westinghouse 19B ("Yankee") engine, rated to give a test stand thrust of 1365 lbs. This amounts to some 1400 Hp. at

450 M.p.h. and 1700 Hp. at 550 M.p.h., sea level. The basic diameter of the engine is 19 in., the weight, complete with all accessories for aircraft use, slightly over 800 lbs. The rotating elements—the compressor and the turbine—whirl at a maximum speed of 18,000 revolutions per minute. At this speed the blades travel at rifle bullet velocities of a round 1200 ft./sec. At such velocities the centrifugal force on each blade amounts to 50,000 times the weight of the blade.

The engine swallows air at the rate of 30 lbs. per second, corresponding to something like a million cubic feet per hour.

As the air enters the engine, it first performs an important little chore in cooling the oil, used for the lubrication of the three main bearings of the engine. The aluminum oil cooler is located in front of the engine where it is subject to cooling air whenever the engine runs, independent of whether the airplane is flying or on the ground.

The 3400 Hp., six stage axial flow compressor pumps up the air to about three times atmospheric pressure in about .004 seconds. The compressed air then enters through the perforations of the annular combustion chamber. Fuel is brought in through rows of atomizing spray nozzles. Spark ignition is used, but as soon as the fuel is burning the ignition system can be turned off because combustion is then continuous.

The air particles spend only .01 second in the combustion chamber. In this short time the energy released per cubic foot by the fuel is about 1000 times as much as in the conventional power plant boiler.

The combustion products enter the turbine at temperatures up to 1500 deg. F. In the turbine they give off about two-thirds of their useful energy to drive the compressor. The jet emerges from the exhaust nozzle of the engine with a velocity of around 1200 miles per hour.

The 19B engine carries accessories to serve the aircraft as well as accessories necessary for the operation of the engine. The accessories are mounted on a gear case where they are easily accessible. They can be located on top, on either side, and at the bottom of the engine, wherever they can be faired in best within the contour of the airplane.

The engine accessories consist of—

(1) An electric starter to bring the engine up to the speed at which it can maintain operation.
(2) A fuel pump to deliver fuel to the combustion chamber.
(3) An oil pump to circulate the lubricating oil.
(4) An overspeed control to prevent the engine from "Running away."
(5) An electric tachometer to give a visual indication of R.p.m. to the pilot.

The aircraft accessories are—

(1) A generator to provide electric current.
(2) A hydraulic pump to furnish high pressure oil to operate landing gear, wing flaps, etc., or a vacuum pump to operate the aircraft instruments.

The Westinghouse 9.5A engine, shown in Fig. 7, is in many ways a small model of the 19B engine. As its name indicates, its diameter is only 9.5 inches. Its static thrust is 275 lb. and its weight is 145 lbs. The top speed is 34,000 revolutions per minute. The engine has anti-friction bearings lubricated by an oil mist (fine oil particles carried by compressed air). The 9.5A engine is equipped with an all-speed control.

The 19B engine came to test first in April 1944. The 9.5A engine followed in June 1944. Further improvements are made almost day by day with the result that, at this time, engines of this same type are counted the lightest and most efficient in the United States and, for the same power, the smallest in the world.

Evaluation of Engines.

In general aircraft gas turbines are evaluated in the same way as up and down engines, fuel consumption, weight, and size being the most important characteristics.

It is interesting to compare the German engines, which have received a great deal of publicity, with the engines produced in this country. The

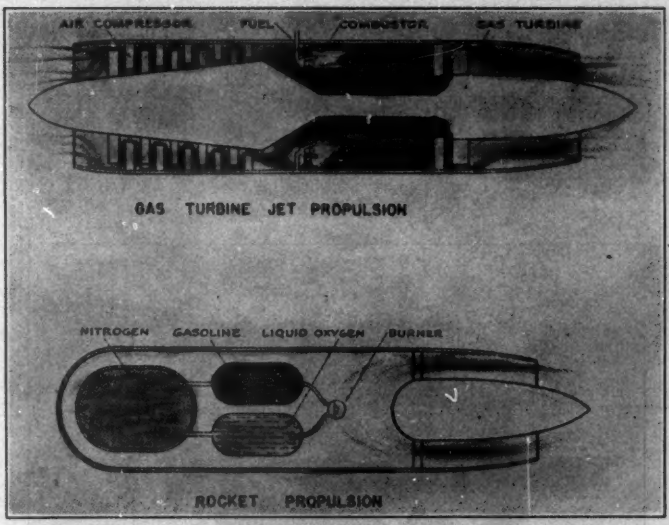

FIGURE 1—SCHEMATIC DIAGRAM OF ROCKET AND JET ENGINE.

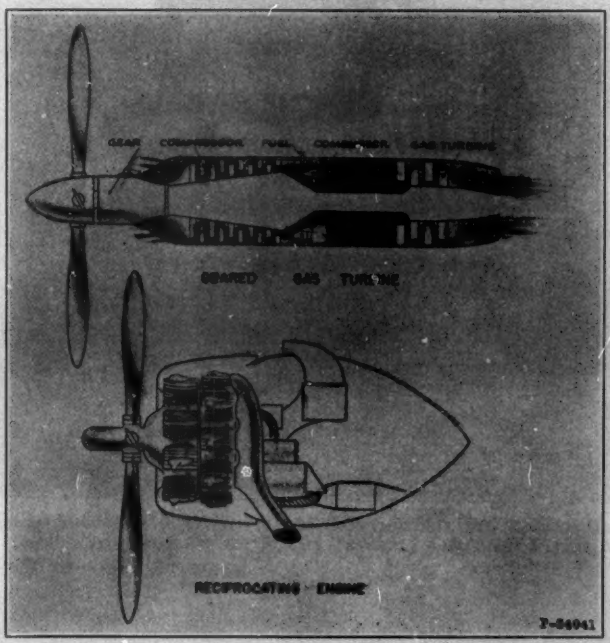

FIGURE 2—PISTON ENGINE AND GAS TURBINE PROPELLER DRIVE.

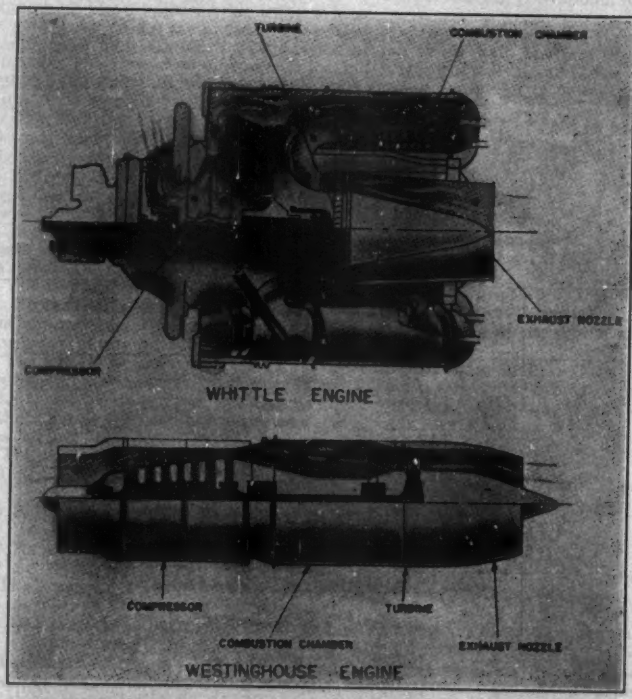

FIGURE 3—WHITTLE CENTRIFUGAL JET ENGINE (TOP) AND AXIAL FLOW JET ENGINE (BOTTOM).

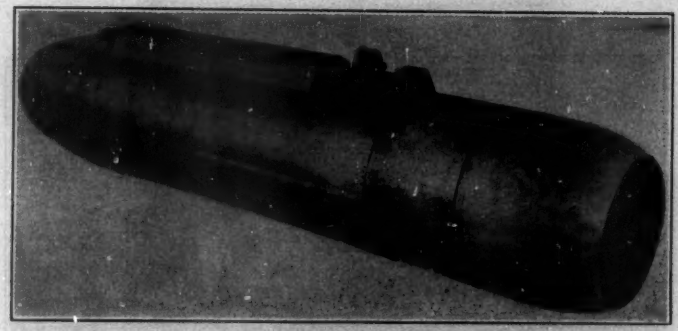

FIGURE 4—19A AXIAL FLOW JET PROPULSION ENGINE.

FIGURE 5—NAVY "CORSAIR" FIGHTER CARRYING THE 19A ENGINE UNDERNEATH THE FUSELAGE FOR FLIGHT TESTING. THE FIRST FLIGHT MADE IN JANUARY 1944.

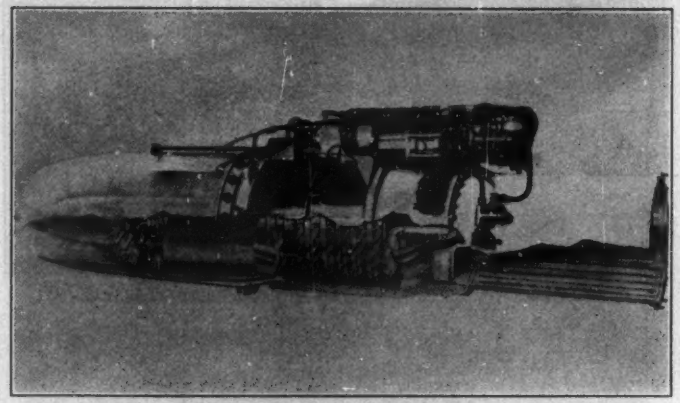

FIGURE 6—CUT OPEN VIEW OF 19B AXIAL FLOW JET ENGINE.

FIGURE 7—OUTSIDE VIEW OF 9.5A AXIAL FLOW JET ENGINE.

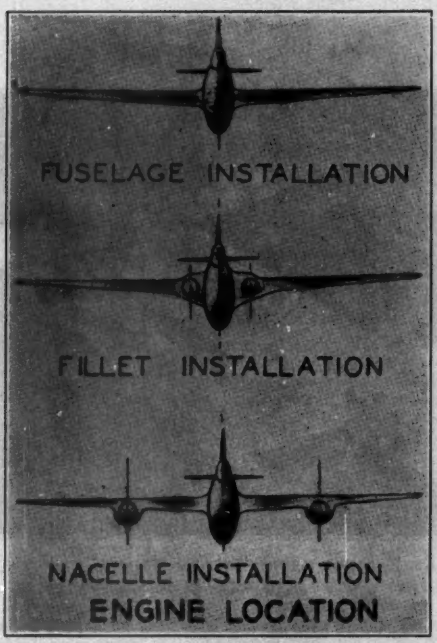

FIGURE 8—THREE TYPES OF JET ENGINE INSTALLATIONS.

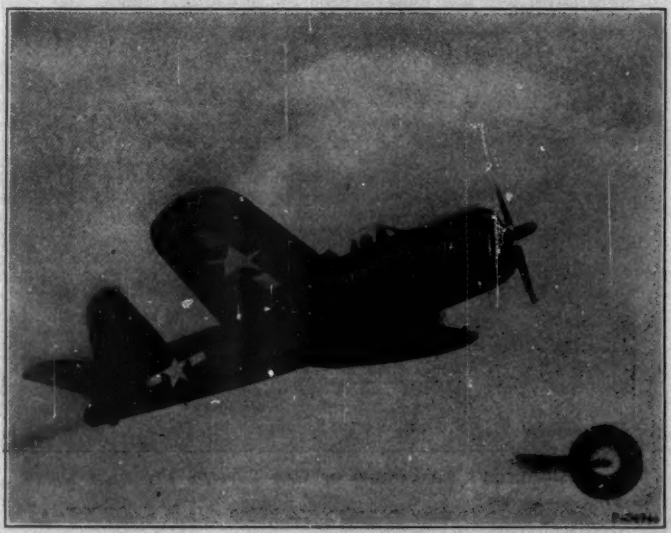

FIGURE 13—RYAN "FIREBALL" NAVY FIGHTER, EXAMPLE OF COMPOSITE POWER PLANT (PISTON ENGINE-PROPELLER DRIVE AND JET ENGINE).

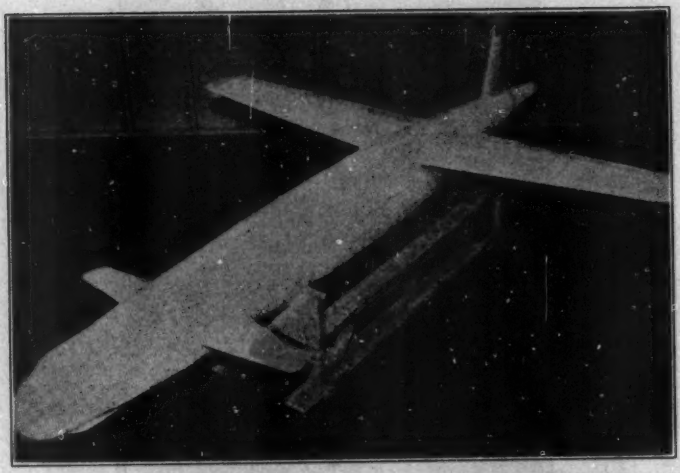

FIGURE 14—AN EXAMPLE OF THE "GUIDED MISSILE," THE NAVY'S "GORGON".

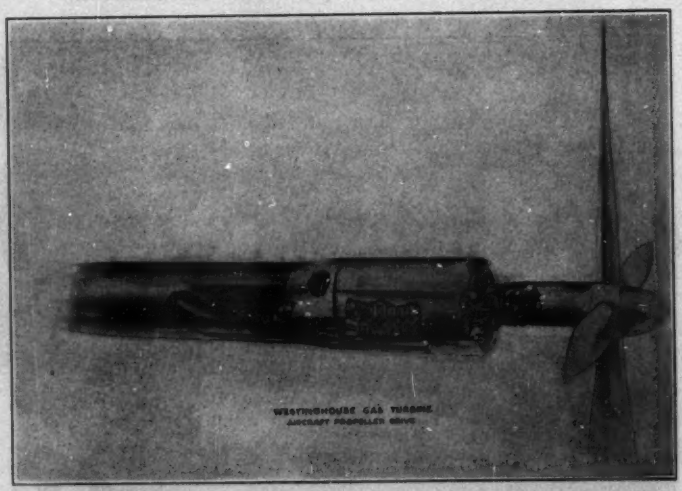

FIGURE 15—ARTIST'S CONCEPTION OF GAS TURBINE PROPELLER DRIVE.

Germans have done a creditable job of getting engines into the air with limited means, particularly with a very limited choice of high temperature alloys. In their designs they have applied a few ideas that we can well afford to take over. But, largely because of material limitations, the Germans had to go to complicated means of cooling and low stresses resulting in large engines. Altogether the weights of the German engines run 1½ to 2 times as high as those of American engines of about the same power. Because of the large amount of compressed air used for cooling, some 15–20 per cent more fuel was consumed. On the basis of the same power the diameter of the German engines is 25 per cent larger than that of the engines which are shown in this article.

Coordination of Aircraft and Engine.

Jet engines can be mounted within the fuselage, in the fillet of the wings or further out along the wing (Fig. 8). Contrary to the piston engine-propeller combination, the jet engine usually passes air all the way through the vital construction members of the airplane, such as the fuselage or the wing.

In any jet application close cooperation of aircraft builder and the engine designer is, therefore, of the greatest importance. After all, it is the combination that is either a success or a failure.

The question of overall performance is, of course, a vital one. Any jet engine, whether it is axial or centrifugal, is sensitive to inlet and exhaust conditions. A 10 per cent loss in total pressure at the engine inlet results in a 20 per cent loss in thrust. Wherever ducting is needed, such as in a fuselage installation, it must be carefully designed so that it will not ruin engine performance and thereby the overall performance of the aircraft.

By way of example, let us take a high speed fighter with a short inlet duct to the engine. For an airplane of this sort the builder will want to use a small inlet area for the duct. The engine designer on the other hand may inadvertently be thinking in terms of a fairly large diameter for his compressor inlet to keep his internal losses low. Unless the two get together at an early stage, the aircraft builder may be forced into trying to make a duct that diverges too rapidly, resulting in low duct efficiency and poor performance.

Flight Performance Characteristics.

The jet engine serves essentially to produce a stream of hot gases with high velocities. It has been called a "hot gas generator."

The forward thrust exerted by the engine is a direct result of the change in momentum of the air mass absorbed by the engine. Forces are needed to accelerate the air particles through the engine. It is the reaction to these forces which we call thrust.

To investigate how the thrust of the engine varies as the flight speed increases, we must know what happens to the mass of air transported through the engine and what happens to the inlet and exit velocities of the medium.

As Fig. 9 indicates, with increasing flight speed the air in front of the engine becomes more and more compressed due to the "ram" effect. Therefore, at the same R.p.m. and with denser air, the transported mass *increases* as the plane goes faster.

Since the engine thrust is the product of mass and velocity increase, the thrust (as shown in Fig. 10 for an average case) remains substantially constant over a wide speed range. This means that the power delivered by a jet engine goes up almost directly with the speed of the plane. This explains that jet propulsion should not be applied to low speed aircraft.

If we now compare this performance with that of a variable pitch propeller—be it driven by a reciprocating engine or by a gas turbine—we find that such a drive will give substantially constant power over a wide range of speed. At take off such a propeller drive will give some three times the thrust realized at maximum speed.

These facts disprove the popular misconception that jet planes have a phenomenal take off—quite the opposite is true. On the basis of the same

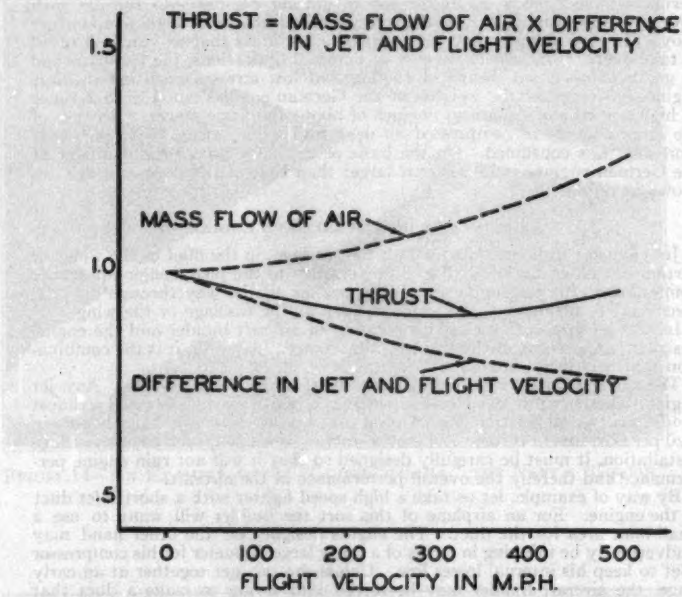

FIGURE 9—VARIATION OF JET ENGINE THRUST WITH SPEED.

power at high speed, the take off thrust of the jet engine is considerably less than that of a propeller drive and a longer take off distance is needed.

What has confused most people is that the jet engines that can be made available for aircraft such as small fighters are so high powered that their take off is still acceptable. However, if the same horsepower could be put into a propeller drive the take off distance would be even much less.

It is also of interest to compare the jet engine and the variable pitch propeller drive on the basis of efficiency (fuel consumption).

Since the amount of fuel does not vary a great deal with flight velocity it is mostly a question of heating up the air mass to a safe limiting temperature—the jet engine efficiency will vary more or less with the power output, and as we have seen for speeds up to 800 M.p.h. the power output varies almost directly with the speed of the plane. Therefore, the efficiency of the jet engine increases as the plane goes faster (Fig. 11). On the other hand, with a variable pitch propeller and for a given power, the efficiency of the drive remains substantially constant over a wide speed range until propeller tip velocities are reached that are in the range of the velocity of sound. Then the efficiency drops abruptly. There is a point, at perhaps 550 M.p.h., where the jet engine efficiency exceeds that of the propeller drive. It is beyond this point that the jet engine really comes in to its element.

The altitude performance characteristics of the gas turbine, compared with those of the reciprocating engine (with and without supercharging) are indicated in Fig. 12.

The aircraft gas turbine as such cannot be supercharged. Hence the variation of engine output with altitude is very similar to that of the unsupercharged piston engine. That the gas turbine output does not drop off as

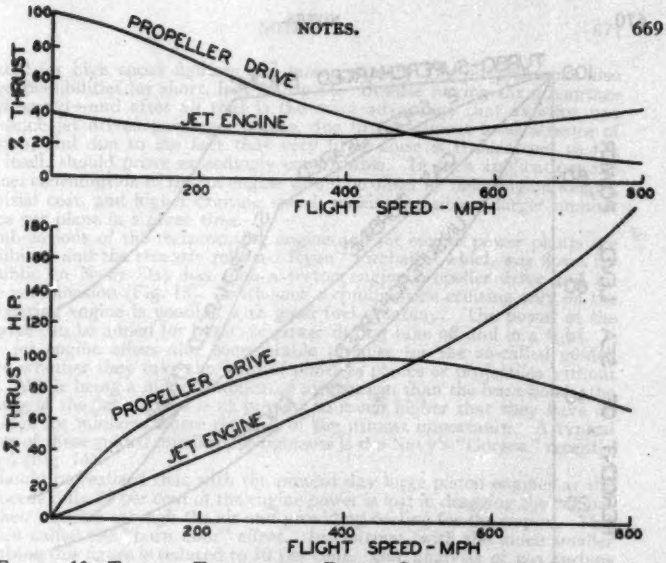

FIGURE 10—TYPICAL THRUST AND POWER CURVES OF JET ENGINE AND PROPELLER DRIVE FOR HIGH SPEED AIRCRAFT.

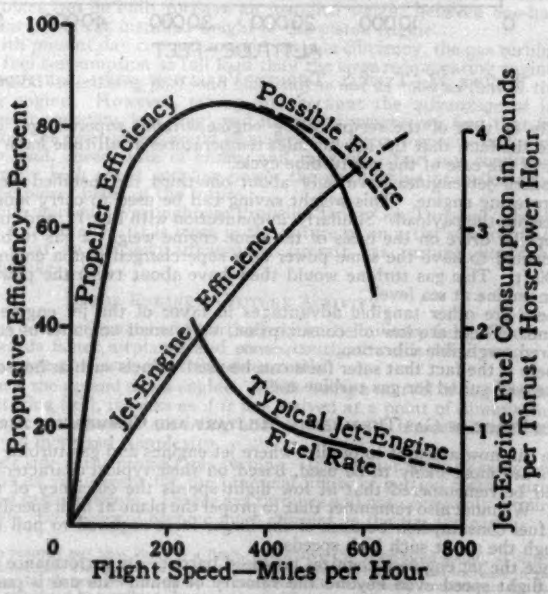

FIGURE 11—EFFICIENCY CURVES FOR PROPELLER AND JET ENGINE.

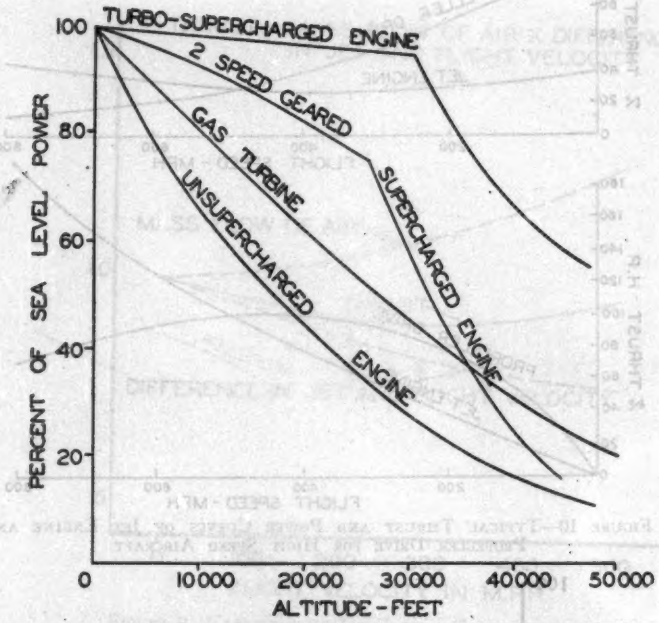

FIGURE 12—TYPICAL THRUST VARIATION WITH ALTITUDE.

rapidly as that of the reciprocating engine without supercharger is largely due to the fact, that the low air inlet temperatures at altitude have a greater effect in the case of the gas turbine cycle.

Modern jet engines have only about one-third the installed weight of a reciprocating engine. This weight saving can be used to carry more fuel or to increase the payload. Similarly, in connection with Fig. 12, and considering a propeller drive on the basis of the same engine weight a gas turbine could be selected to have the same power as a supercharged piston engine at say, 40,000 ft. This gas turbine would then have about twice the power of the piston engine at sea level.

There are other tangible advantages in favor of the jet engine and gas turbine. These are low oil consumption, very small amounts of cooling air required, negligible vibration.

There is the fact that safer fuels can be used. Fuels such as household fuel oil are well suited for gas turbine use.

THE PLACE OF GAS TURBINES IN MILITARY AND COMMERCIAL AIRCRAFT.

We can now attempt to predict where jet engines and gas turbine propeller drives are most likely to be used, based on their typical characteristics. It should be remembered that at low flight speeds the efficiency of the jet is poor. We must also remember that to propel the plane at high speeds requires high fuel consumption because of the larger force required to pull the plane through the air at such high speeds.

Since the jet engine recognizes no speed barrier—its performance improves with flight speed even beyond the velocity of sound—its use is particularly

indicated for high speed fighters and interceptors.* The jet plane has also decided possibilities for short, fast transport. Besides having the advantage of high speed—and after all that is the main advantage that aviation can offer—such jet driven passenger planes, due to the almost total absence of vibration, and due to the fact that very little noise is transmitted to the plane itself, should prove exceedingly comfortable. In such applications the high fuel consumption of the jet engine would be offset by light engine weight, low initial cost, and higher cruising speed, making possible a larger number of trips per plane in a given time.

Combinations of the reciprocating engine and jet engine power plants are a possibility and the recently released Ryan "Fireball," which was flown for the public on Navy Day has such a piston engine propeller drive and jet engine combination (Fig. 13). With such a combination cruising only on the reciprocating engine is possible with good fuel economy. The power of the jet engine can be added for bursts of power during take off and in a fight.

The jet engine offers also considerable promise for the so-called guided missiles whether they take the form of pilotless planes or projectiles without wings. While being a more complicated mechanism than the buzz-bomb, the efficiency of the jet engines is at present so much higher that they have an advantage for missions where range is of the utmost importance. A typical example of these guided missile developments is the Navy's "Gorgon" recently released (Fig. 14).

It should be realized that with the present day large piston engines at the high speeds fully 30 per cent of the engine power is lost in dragging the engines with their nacelles through the air and providing cooling for the engine. This has been called the "barn door" effect. In contrast, with the much smaller gas turbine this figure is reduced to 10 per cent. Our analysis of gas turbine propeller drives has proven that gas turbines can be built with only one-half the diameter of the reciprocating engine for the same power. We are confident that gas turbines can be built to have an installed weight between one-half and three quarters of the installed weight of the piston engine.

Already with present day compressor and turbine efficiency, the gas turbine has a better fuel consumption at full load than the large reciprocating engine. On the test stand its cruising part load efficiency is not as good as that of the reciprocating engine. However, taking into account the advantage of its smaller diameter (meaning less drag) and its lighter weight, we find that for a large airplane the gas turbine would be superior in every respect—including range or pay load, speed, rate of climb, and take off. For any conditions except extremely high speed and low power the gas turbine propeller drive appears as the power plant of the future.

Fig. 15, while marked "Westinghouse Propeller Drive Gas Turbine," should not be taken too literally. It is more in the nature of an artist's conception. It indicates what an efficient streamlined aircraft gas turbine would be expected to be like.

Large Engines—Future Activity.

Throughout aviation history and particularly in the military field, the trend has been towards faster airplanes and consequently towards more powerful engines. We have now arrived at the cross roads.

On one side is the up and down engine. While being a marvel of engineering and manufacturing skill, it looks as if it has arrived at a point of diminishing returns. Larger horsepowers are being bought only with increased numbers of cylinders and increased complexity.

On the other side is the aircraft gas turbine. It does not seem to recognize any size limits as yet, except for the practical limits of getting certain sizes of forgings and castings made. Larger gas turbines will not necessarily require any more parts and they will become more efficient as the size increases.

* It should be pointed out that there is a limit, well above the velocity of sound, at which the temperature increase due to the ram effect is so great that the additional increase in the compressor brings the air temperature up to the maximum allowable peak temperature for the engine. Thus it would not be possible to burn any fuel without exceeding this temperature limit.

Further increase in flight speed will favor the jet engine. Further increase in power will favor the aircraft gas turbine in jet or propeller drive form.

Already today there is demand for engines of 6000 Hp. and 10,000 Hp. The Germans built an 8000 Hp. jet engine. A piston engine for such powers would be a very difficult piece of machinery to build, and it is doubtful if its size and complexity would not be prohibitive. But we see no reason at all why jet engines or gas turbines of 6000 or 10,000 Hp. cannot be built immediately.

There is no question but that gas turbine development is still in its infancy. So far, only the simplest form of turbo-jet has been worked out in a practical manner. There is no question but that, within a very few years, there will be refinements added—intercoolers, reheaters, heat exchangers. The properties of the jet engine will be utilized for high speed maneuvering and to perform chores like cabin heating and de-icing.

Within the framework of this article, there has not been the space to include metallurgical considerations, combustion problems, aerodynamics of turbine and compressor blades, high speed bearing developments and many other subjects, each of which is fascinating for its own sake. Yet the picture is not complete without a realization, how enormous a field of research is to be covered, and how intensive the research must be to make good the promise that the aircraft gas turbine holds out. This need is recognized by the Armed Services. It calls for a good deal of effort from organizations like the N.A.C.A. and the Bureau of Standards, besides that of the industrial concerns which are devoting a large part of their research effort to this development. It is only with such intensive and coordinated research that a leading position in this field can be retained.

BOOK REVIEW.

TABLES OF FRACTIONAL POWERS, By The Mathematical Tables Project under the sponsorship of the National Bureau of Standards. Published by the Columbia University Press, New York, N. Y.

This compilation of mathematical tables consists of two parts; the first, a series of tables of A^x for fixed bases and variable exponents and, the second, a series of tables of X^a for variable bases and the frequently occurring exponents $\pm \frac{1}{2}$, $\pm \frac{1}{3}$, $\pm \frac{2}{3}$, $\pm \frac{1}{4}$, $\pm \frac{3}{4}$ and a table of values for $X = 0$ to 9 and $a = .01$ to .99.

ELECTRONS, ATOMS, MOLECULES, By Dr. Albert Cushing Crehore. Published by the Christopher Publishing House, Boston, Mass.

In this book Dr. Crehore sets forth his own theory of the atom presenting an entirely new conception of the forms of atoms in their steady states.

THE METALLURGY OF STEEL CASTINGS, By Charles Willers Briggs, McGraw-Hill Book Company, New York, New York.

This book provides a single source reference of detailed information on technical and metallurgical control in steel casting production, providing buyers of steel castings, design engineers, metallurgists of other industries, students, technical and operating men of the steel casting industry with a concise understanding of the manufacture and quality control of steel castings. It is a number in the Metallurgical Engineering Series of McGraw-Hill Book Company.

NAVAL ARCHITECTURE OF PLANING HULLS, By Lindsay Lord. Published by the Cornell Maritime Press, New York, N. Y.

This book is a complete naval architectural study of fast sea-going power boats of the planing type. It attempts to lift the art of small boat design into the scientifically exact field usually reserved for large vessels of the displacement type. The author correlates a wealth of information and experience which he gained by intimate association with the design of Army, Navy, and Coast Guard small boats during the war.

SERVICE NOTES.

In a recent booklet published by the United States Coast Guard entitled "A Plan for the Procurement and Education of Coast Guard Officers," a report of a special committee appointed to study this subject is contained. It outlines briefly the duties and history of the Coast Guard as a background for the studies and then proceeds to make specific recommendations for the selection of candidates for and education of Cadets to meet the officer requirements. This is followed by a comprehensive proposal for post graduate education and a planned career for officers. The booklet should be of great interest to those engaged in procurement of not only officers for the Naval and Coast Guard Service but also engineers for industry.

WEBB INSTITUTE INFORMATION.

1. Students at this school have no expenses. They are furnished board, lodging, tuition, books, instruments, etc., and laundry free of charge.
2. Students have a 10 weeks practical work period each winter, either at sea or in a shipyard or machine plant; the Institute endeavors to place the students and they receive pay while at work.
3. Students must be between 16 and 21 years of age at the time of the June examinations; they must be unmarried, be American citizens and in good health. *Age limits may be waived for veterans.*
4. Applicants must have completed the equivalent of a High School Course as follows:

   4 years of English
   3 years of a foreign language (or 2 years in each of 2 foreign languages—a total of 4 years)
   1 year of Physics
   2 years of History (1 of which must have been in American History)
   1½ years of algebra

1 year of Plane Geometry
½ year of Solid Geometry
½ year of Plane Trigonometry

In addition to the above, applicants must have enough points to give them a total of 16 points at the time of examination.

5. Applicants should not wait till they have completed their last year of High School but should make their application at once and state they are making up any deficiencies that exist.
6. The school grants the degree of Bachelor of Science on graduation.
7. Members havings sons who are interested in this school should *communicate directly with the school and not with the Society.* The address is (after December 1):

Webb Institute of Naval Architecture
Crescent Beach Road
Glen Cove, Long Island, New York

ASSOCIATION NOTES.

ADDRESSES.

It is again urged that each member keep the Society informed of his correct address.

ANNUAL MEETING AND NOMINATIONS TO OFFICES FOR 1947.

The Annual Meeting of the Society was held in Washington, D. C., on Tuesday, 1 October, 1946, pursuant to its By-Laws.

The following nominations for offices for the calendar year 1947 were made:

For President:

Rear Admiral C. W. Styer, U. S. N.

For Secretary-Treasurer:

Captain F. W. Walton, U. S. N.
Captain J. E. Hamilton, U. S. N.

For Member of Council:

Rear Admiral N. L. Rawlings, U. S. N.
Captain D. R. Hull, U. S. N.
Captain R. L. Swart, U. S. N.
Captain A. G. Mumma, U. S. N.
Captain K. K. Cowart, U. S. C. G.
Commander R. D. Schmidtman, U. S. C. G.
Commander W. H. Spowers, Jr., U. S. N. R.
Commodore H. C. Shepheard, U. S. C. G. R.
Mr. C. G. Cooper.
Mr. H. E. Carleton.

Ballots have been distributed. Polls close at 3:30 p. m., on Thursday, 26 December, 1946.

ANNUAL BANQUET.

It was voted to hold a banquet of the Society during 1947.

SOCIETY LAPEL BUTTON.

Shown below is an illustration of the lapel button of the Society. It is believed that it will be conceded that this is a very fine, dignified insignia. It is one-half inch in diameter.

The oak leaves and lettering are red on a gold back-ground. It is available to all members at fifty cents (50c) each.

Prize Essay for 1946.

Technical essays are invited from any member of the American Society of Naval Engineers, any Navy or Coast Guard officer or enlisted man, regular or reserve, on any of the following subjects:

1. The Future of Combustion Gas Turbines for Ship Propulsion.
2. The Future of Diesel Engines for Ship Propulsion.
3. The Future of Steam Turbines for Ship Propulsion.
4. The Comparative Merits of Combustion Gas Turbines, Diesel Engines and Steam Turbines for Ship Propulsion.
5. Modern Trends in Hull Design and Construction.
6. Influence of Arctic Operations on Future Ship Design.
7. The Use of Special Alloys in Ship Design.

Articles must be received by the Secretary-Treasurer, American Society of Naval Engineers, Navy Department, Washington, D. C., by 31 January, 1947. Prizes of $500, $300 or $200 may be awarded for a paper considered by the Council to warrant such awards. Those papers awarded prizes will be considered the property of the Society and may be published in the JOURNAL without further payment. If so published, due credit will be given to the author. If other papers submitted in the contest are published in the JOURNAL, they will be paid for at the prevailing publication rates. All other papers will be returned.

In judging articles first consideration will be given to technical contents. English composition, originality of contents, analysis of problems presented, and possibilities of practical application of conclusions reached are also factors to be considered.

The length of the article is not restricted, but one in the order of 5000 words is suggested.

Considerable latitude in treatment of the subject selected is permissible. For example, if a contestant is particularly conversant with one phase of a problem covered in the above seven subjects, a paper confined to that one phase would not be ruled out. Supporting engineering data may or may not be included at the option of the contestant.

Any article submitted in accordance with the above rules must be plainly marked to indicate that it is submitted in competition for the Prize Essay Award.

Annual Meeting of the Society for Experimental Stress Analysis.

The Annual Meeting of the Society for Experimental Stress Analysis, including a Symposium on Telemetering of Aircraft Flight Observations, will be held at the Hotel New Yorker, New York, N. Y., on December 9, 10 and 11, 1946. Inquiries should be addressed to the Society, P. O. Box 168, Cambridge 39, Mass.

Membership.

Attention of all non-member officers is especially invited at this time to the advantage and benefit to be attained by membership in this Society. The Society was organized in 1888—for the sole purpose of the advancement of Engineering. Its Journal, published quarterly, in February, May, August and November, and completing its 58th year of continuous publication, has attained a foremost rank in its field and is a recognized authority throughout the engineering world. It is used generally by Naval officers and civilians alike as a reliable reference book. The Bureau of Ships considers the Journal of such value that it makes it available for the libraries of all Naval vessels and shore activities of any size. The presence of the Journal in your personal library cannot fail to be of great benefit to you, often making available information of great value which can be obtained from no other source.

It is particularly suggested that officers of the Naval Reserve, who are returning to civil life, should arrange for membership prior to detachment from active duty.

Annual dues are $5.00, which are probably lower than those of any other technical Society. There is no initiation fee, nor any

extra charge for the JOURNAL. This extremely low cost is possible only because the Society is bona fide operated solely for your benefit without any pecuniary profit to any one.

An application blank generally will be found at the back of each copy of the JOURNAL. However, if none is found, application by letter will be accepted.

It is suggested that Members will confer a real favor on non-members by bringing the Society to their attention.

MEMBERSHIP ADDITIONS.

The following have joined the Society since the publication of the August, 1946, JOURNAL. Addresses of personnel on ships not given:

NAVAL.

Andrews, Harold J., Lieut., j.g., U. S. N. R.
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Belt, John R., Lieut., j.g., U. S. N. R.,
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Mail 3204 Piedmont Ave., Baltimore 16, Md.

Boomer, G. C., Lieut., U. S. N.

Carnahan, Donald G., Ensign, U. S. C. G.,
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Cartwright, Stephen P., Lieut., U. S. N.,
P. O. Station A, Box 1376, Bremerton, Wash.

Chipley, George W., Commander, U. S. N. R.
Central Station and Marine Dept., Allis-Chalmers Mfg. Co., Milwaukee 1, Wis.

Chirillo, Louis D., Lieut., j.g., U. S. N. R.

Connell, William F., Ensign, U. S. N. R.

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Cullen, Matthew A., Jr., Lieut., U. S. N.

Drea, Andrew R., Lieut. Commander, U. S. N.

Dunning, Bruce B., Lieut., j. g., U. S. N.

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Knight, Harry F., Jr., Ensign, U. S. N. R.,
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Mail 2059 Park Road, N.W., Washingtin 10, D. C.

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care British Embassy, Washington, D. C.

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